CIVIL ENGINEERING RESEARCH

A COMPARISON BETWEEN CONVENTIONAL AND LANDSAT-BASED HYDROLOGIC MODELING THE FOUR MILE RUN CASE STUDY

FINAL

by

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October, 1976

for the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

Many of the models designed to support the hydrologic studies associated with urban water resources planning require input parameters that are defined in terms of land cover. Estimating the land cover is a difficult and expensive task when drainage areas larger than a few sq. km are involved. The purpose of the reported investigation was to compare conventional and Landsat-based methods for estimating the land cover based input parameters required by hydrologic planning models. Comparisons were based on a case study of the 50.5 sq. km (19.5 sq. mi) Four Mile Run Watershed in Virginia. Results of the study indicated that the Landsat-based approach is highly cost-effective for planning model studies. The conventional approach to define inputs was based on 1:3600 aerial photos, required 110 man-days and a total cost of $14,000. The Landsat based approach required 6.9 man-days and cost $2,350. The conventional and Landsat based models gave similar results relative to discharges and estimated annual damages expected from no flood control, channelization, and dentention storage alternatives.

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Gentlemen:

Attached are two copies of the report "A Comparison Between Conventional and Landsat/Based Hydrologic Modeling-The Four Mile Run Case Study". This is a final technical report describing the activities associated with NSG5017 for the 1975-76 fiscal year. Three additional copies have been given to Dr. Vincent V. Salomonson, the NASA Technical Officer for the Project.

Very truly yours,

Robert M. Ragan
Professor
Project Director

RMR:gww
enclosures

A COMPARISON BETWEEN CONVENTIONAL AND LANDSAT-BASED HYDROLOGIC MODELING - THE FOUR MILE RUN CASE STUDY

PROJECT REPORT

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RESULTS and CONCLUSIONS

The Four Mile Run Study provided an opportunity to test the untility of Landsat Multispectral Scanner (MSS) data as a tool in urban water resources planning. Testing was implemented as part of a watershed planning program being conducted by the consulting engineering firm of Water Resources Engineers, Inc. (WRE) for the Northern Virginia Planning District Commission (NVPDC). While some limited experiments were conducted with the design model WREM, emphasis was on the use of Landsat to define parameters required for operation of the hydrologic planning model, STORM. The approach was for WRE to meet their responsibilities to their client by operating STORM with parameters defined from conventionally developed land cover inventories and calibrated to recent streamflow records. WRE then operated STORM under the simulated condition that the watershed was ungaged and that Landsat MSS data had been used for parameter definition. The 50.5 sq. km (19.5 sq. mi) Four Mile Run was an especially attractive arena for conducting the tests because extensive hydrologic, economic and land cover data were available. These data allow meaningful interpretations to be assigned to differences in the results obtained with the conventionally and Landsat defined models.

A. Results

1. The watershed percents of imperviousness estimated from the conventional and Landsat land cover delineations were 34.6 and 39.1 respectively.
2. Both conventional and Landsat-based versions of STORM produced simulated flood flows that were in excellent agreement with recent observed peak discharges. The Landsat based peak flow estimates averaged 4.8% lower than those obtained with the conventional version of STORM.

3. The synthetic flood frequency curves developed with the two versions of STORM were essentially the same in the vicinity of the 100 year flow. The Landsat based flood flows were slightly higher than the conventional estimates for the more frequent events.
4. Estimated annual damages without any flood control facilities were \$3,140,500 and \$2,761,700 for the conventional and Landsat versions of STORM. When the USACE flood control facilities were programmed into the two versions of STORM, the estimates of annual damages were reduced to \$89,900 and \$86,500. Simulations of the impacts of different levels of detention storage were essentially the same for the two versions of STORM.
5. Development of the input data needed for the operation of STORM from 1:3600 color aerial photographs and field surveys required approximately 110 man days and cost \$14,000. Development of STORM inputs using computer aided classification of Landsat MSS data and limited photographic sampling required 6.9 man days and cost \$2,350.
6. Efforts to use Landsat to reproduce conventionally estimated percents of imperviousness and peak flows with WREM for 179 subwatersheds within the Four Mile Run Basin were unsuccessful. However, acceptable agreement between the two approaches was obtained for those subunits having drainage areas approaching one square mile or larger.

B. CONCLUSIONS

The results of the Four Mile Run and other studies cited in the text lead to the following conclusions:

1. Computer aided classification of Landsat MSS data, supported with limited air photo or field sampling, is an excellent approach for

developing the land cover distributions and parameters required for hydrologic planning models similar in structure to STORM.

2. Except on very small watersheds, the agreement between the hydrologic simulations produced by a conventionally defined model and those obtained from a Landsat based model should be within a range acceptable for watershed planning studies.
3. Significant reductions in the costs and man hours associated with the development of land cover and parameter estimates for hydrologic planning models can be achieved by using the Landsat approach. The magnitude of these reductions is a function of the watershed size and type of "conventional" approach being used. Anticipated cost savings of 50% to 75% appear reasonable.
4. The Landsat approach is especially attractive for application on large watersheds and in situations where a number of watersheds within a jurisdiction are to be studied.
5. The utility of Landsat becomes questionable when small watersheds are involved. Additional research on the problem of watershed size and classification accuracy is needed. Until such research can be completed, a watershed size of approximately one square mile appears to be a reasonable minimum for application of the Landsat approach. The particular circumstances of an organization will also determine some minimum size at which it becomes more economical to use some approach other than Landsat. These circumstances will include such factors as accessibility to the necessary computer facilities, the date and scale of aerial photography, and the salary structure of technician or intern-level personnel.

CHAPTER I

INTRODUCTION

Many of the models designed to support the hydrologic studies associated with urban water resources planning require input parameters that are defined in terms of land cover. The advantage of a model having land cover based parameters is that it allows experimentation with alternate forms of development and the assessment of future changes that might occur. Unfortunately, estimating model parameters in terms of land cover is a difficult task when areas in excess of several square miles are involved. This, any innovation that can reduce the problems of land cover delineation of model parameter definition should be of significant value to the water resources planning community.

Shortly after the launch of Landsat 1, researchers in a number of fields started reporting successful efforts in determining important information from the satellite data. The results reported show that Landsat has a tremendous potential as a tool in hydrology. Still, the findings indicated that there was a need for an comprehensive study in which the impacr of differences between conventional and Landsat data inputs to models could be compared. The comparisons had to be made in a "real world" situation where there was extensive ground truth, supporting hydrologic data, and a mechanism for converting differences in model outputs to economic consequences. The need for these comparisons led to the development of the Four Mile Run Study.

The objective of the Four Mile Run Study was to evaluate Landsat remote sensing as a method of defining input parameters required by urban hydrologic

planning models. This evaluation was implemented as part of the water resource planning being conducted on the Four Mile Run Watershed by the consulting engineering firm of Water Resources Engineers, Inc. (WRE). WRE had been retained by the Northern Virginia Planning District Commission (NVPDC) to conduct a study of the relationship between urban development and flooding for the Four Mile Run Basin. Four Mile Run is a heavily urbanized, 50.5 sq. km (19.5 sq. mi) watershed in the Virginia suburbs of Washington, D.C. The study was in response to an enabling legislation which authorized a Flood Protection Project by the U. S. Army Corps of Engineers (USACE) under the condition that the local governments develop plans to insure that future land cover changes would not jeopardize the Project.

WRE used two models to meet the objectives of the study. These models were: 1) STORM (Storage, Treatment, Overvlow, Runoff Model) developed by the USACE (1974); and 2 WREM (WRE Runoff Model) which is an outgrowth of the EPA Storm Water Management Model (1971). STORM is a relatively simple model that is intended as a preliminary planning or screening tool. WREM, on the other hand, is a complex design model intended for detailed analysis in the final decision-making phases of a project.

In evaluating the hydrologic impact of Landsat data, some work was done with WREM, but emphasis was on testing the satellite as a tool for defining parameters required for the operation of planning models such as STORM. The approach was for WRE firm to meet their client responsibilities by operating STORM with parameters defined from detailed land use inventories

and calibrated to recent stream-flow records. WRE then operated STORM under the simulated condition that the watershed was ungaged and that Landsat MSS data had been used for parameter definition. By operating the two versions of STORM in parallel the impact of using Landsat as opposed to conventional input data could be evaluated. The function of the parallel operation was to allow comparison between: 1) the observed peak discharges used for calibration and those estimated by the models; 2) the synthetic flood frequency curves; and 3) the predicted annual damages associated with alternate flood control techniques being considered during the planning phases.

CHAPTER II

LANDSAT AS A TOOL IN HYDROLOGIC STUDIES

A. Overview

Remote sensing, as defined by Reeves (1975), is "the measurement or acquisition of information of some property of an object or phenomena by a recording device that is not in physical contract with the object or phenomena of study." Landsat is concerned with remote sensing of the electromagnetic properties of the earth's surface phenomena. The precise region of the spectrum being investigated is that between 0.5μm and 1.1μm, the visible and near infrared region of the electromagnetic spectrum. Between 0.5μm and 0.1μm Landsat sensors measure light waves reflected from the earth, or more correctly, reflected solar irradiance.

Incoming solar irradiance passes through the vacuum of space and enters the earth's atmosphere where it is attenuated. A portion of the solar irradiance that reaches the earth's surface is reflected by the ground over materials. The amount reflected varies with the particular wavelength and type surface material. Fundamental to Landsat remote sensing is the ability to measure the amount of solar irradiance being reflected within a narrow band of wave lengths. When one compares data from a series of such narrow band measurements, a "spectral signature" is obtained. Ideally, each surface material will have a unique spectral signature which can be described either in terms of the absolute amount of energy reflected or as a percentage. Figure II-1, from Root and Miller (1971) shows the spectral signatures of a

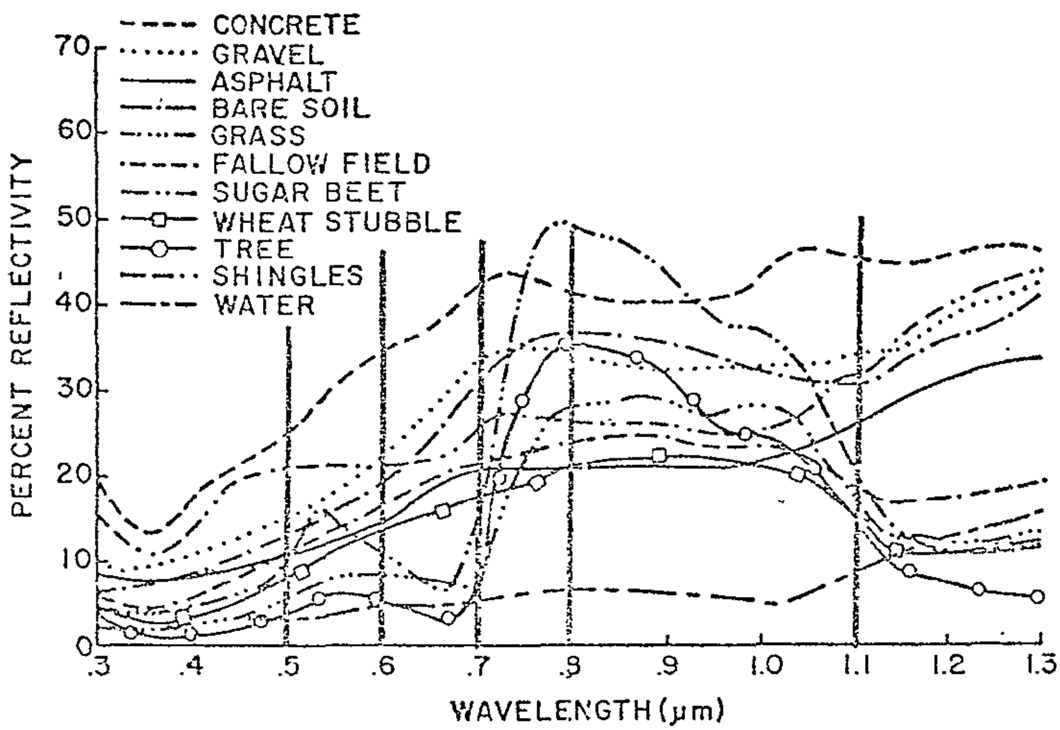


FIGURE II - 1

Mean Spectroreflectance Curves for Eleven Surface Material Categories

(From Root and Miller (1971))

number of surface materials.

Two techniques can be used to obtain remotely sensed data in the spectral region, 0.5 to 1.1 μm: photography and optical scanning. In conventional photographic remote sensing, sensitized film is exposed to the reflected solar irradiance. The film reacts to the energy in proportion to its intensity over the film's sensitive region. On a positive print, the darker the tone, the lower the amount of energy that is reflected by the object in the sensitive region. Lighter tones indicate more reflected energy.

Several cameras, each having film of different characteristics, or several cameras with different filters, can be used to obtain a series of photographs of an area in which each will emphasize reflectance within a specific band. This approach is known as multispectral photography. Referring to Figure II-1 as an example, note that in the region 0.5 to 0.6 μm that asphalt has a moderate response, grass, a low response, and forest has a low response. In the region between 0.7 and 1.1 μm, asphalt is moderate, grass high, and forest low. When a photographic film is exposed in each region, or band, different tones will result. By comparing the tones in different band, information on the material can be inferred.

It is possible to obtain narrow band photographs for numerous spectral regions, however, it is not necessary or even desirable to do so. A few carefully selected bands can provide sufficient data for most uses. If too many bands are used in a multispectral photographic

mission, it becomes difficult for the interpreter to perform the analysis.

Computers can be used to aid in the interpretation of multispectral solar irradiance by using the multispectral scanner (MSS) instead of a photographic system. The MSS uses an oscillating mirror to scan the earth and focus the reflected solar irrandiance from a discrete ground unit onto a series of radiation detectors. Figure II-2 is a schematic of the Landsat MSS. Each detector converts the reflected solar irradiance within a specified wave band into a voltage. The voltage is then converted to a digital form, transmitted, and put onto a computer compatible tape(CCT). Once in digital form, the data can be analyzed and classified by a computer in accordance with some set of decision rules programmed into the system.

B. Landsat Data and Computer Aided Analysis

Landsat 1, launched on July 23, 1972, was used in the Fourmile Run Study. The satellite orbits the earth at a nominal altitude of 910 km (565 miles) fourteen times per day and passes over the same point every eighteen days. Landsat 2, launched on January 22, 1975, carries the same instrument package and orbits such that one of the satellites is passing a given point every nine days. The spectral bands in which measurements are made listed in Table II-I and shown in Figure II-1.

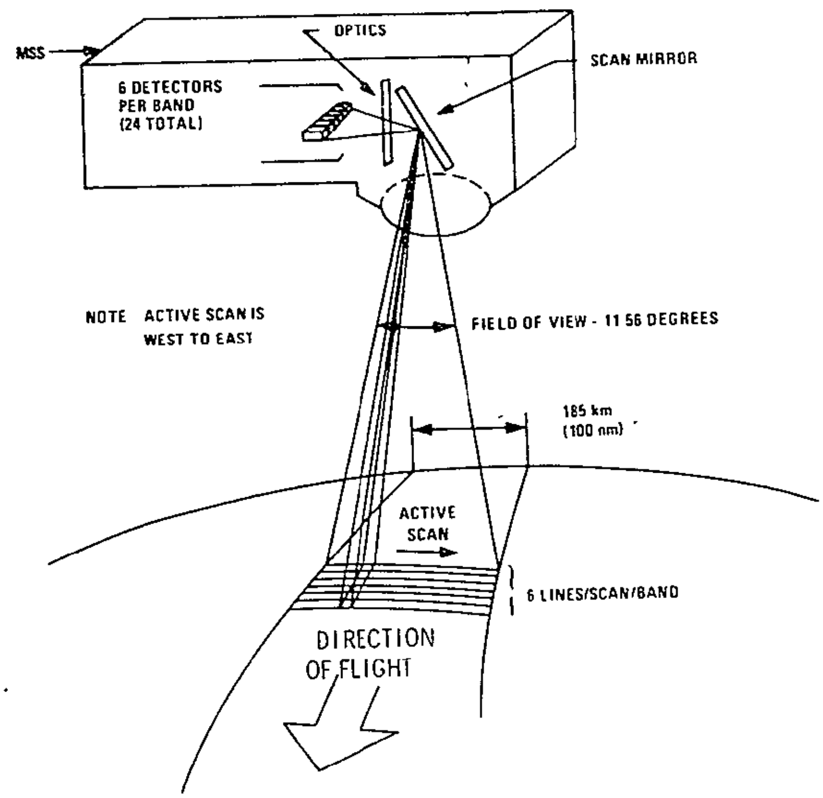


FIGURE II - 2

Multispectral Scanner Subsystem

(from General Electric ERTS-2 Reference Manual)

Table II-I

Landsat Spectral Bands

Band No.	Spectral Interval μm
4	0.5 - 0.6
5	0.6 - 0.7
6	0.7 - 0.8
7	0.8 - 1.1

In the Landsat remote sensing system, the digital MSS data is transmitted from space to one of several ground receiving stations. These ground receiving stations then forward magnetic tapes containing the data to the NASA Data Processing Facility at the Goddard Space Flight Center. There, the data are formatted on a "scene" basis and stored on computer compatible tapes (CCT). A scene is a square section of the earth's surface measuring approximately 185 kn X 185 km (115 miles X 115 miles) and consists of lines (scan lines) of picture elements ("pixels") as shown in Figure II-2. Each pixel represents an area of approximately 1.15 acres and measures 79 m in the direction of the flight and 59 m along the scane line. It should be recognized at this point that the data recorded by the MSS represents the integral of the energy from the pixel for each band and, therefore because of the size, may reflect the

net effect of several land cover categories contained within the pixel.

There are a number of computer programs and specially designed computer systems available for translating the digital data stored on the CCT into a land cover distribution for all or part of the scene. The particular system used in the Fourmile Run Study was the General Electric Image 100 shown schematically as Figure II-3. The Image 100 is representative of a number of commercially developed systems that are available for use at several centers in the U.S. and foreign countries. The system includes a small computer, tape drives, alphanumeric printer, graphics display terminal and an input scanner unit. All of the components are tied into an interactive console which includes a color cathode ray tube(CRT).

The Landsat data are read from magnetic tapes and stored on discs for an area of approximately 40 km by 40 km. The data are displayed in false color on the CRT for visual analysis. The input scanner unit is used to project maps or boundaries onto the portion of the scene displayed on the CRT. This allows political or geographic subdivisions to be scaled and matched to ground control points that can be located on the CRT. The area inside the overlaid boundaries, here a watershed or several watersheds, is thereby isolated from the rest of the scene so that the subsequent maps and statistical information output by the system will apply only to the area of interest.

In using any interactive computer, such as the Image 100, to classify the land cover, the first step is to locate and define the signature for training sites. A training site is an area on the scene in which the

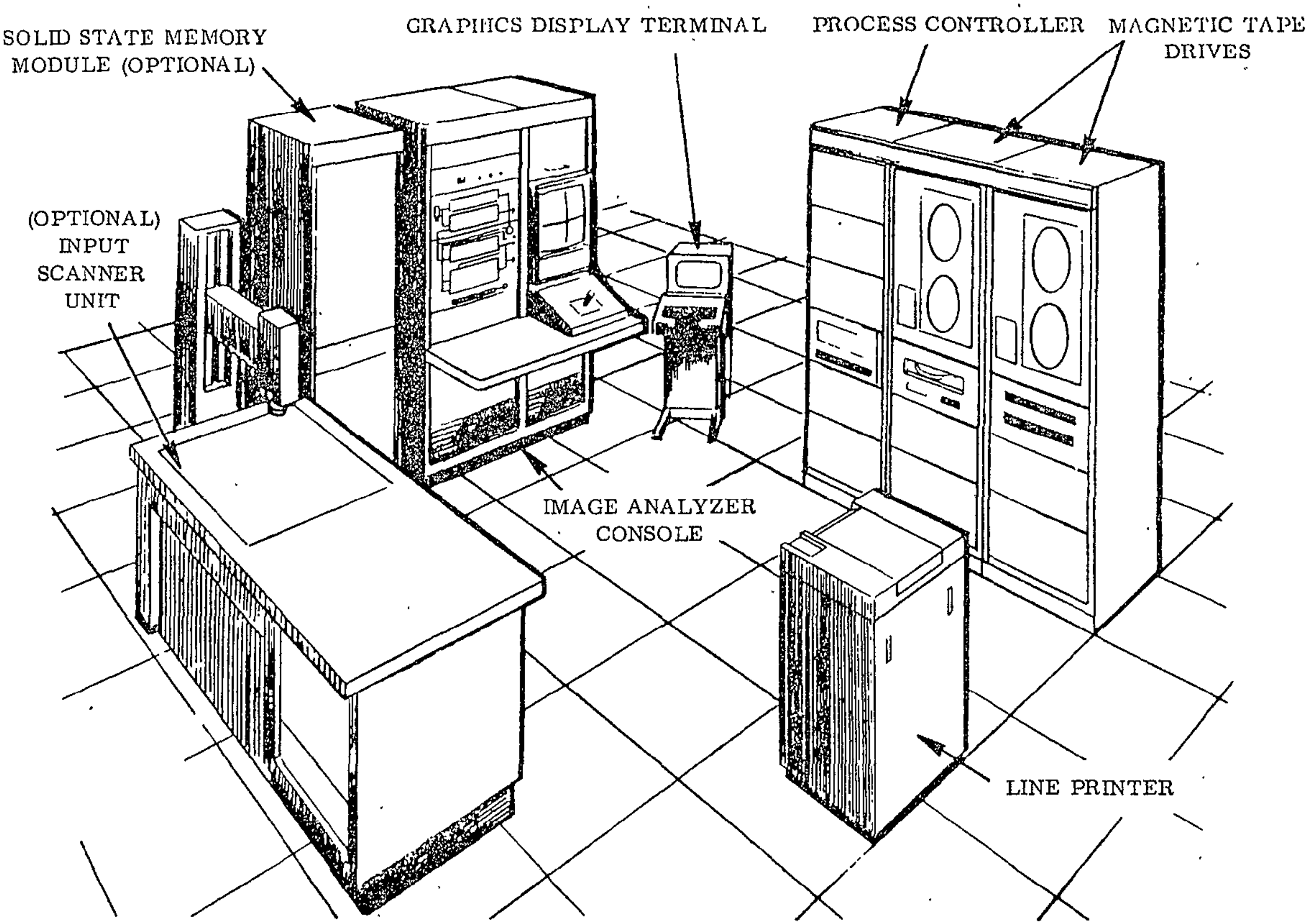


FIGURE II - 3

Schematic of General Electric Image 100

land cover is known. Several training sites for each land cover category of interest are located on the CRT. The Landsat data for each category are then used to establish multidimensional bounds for each class. In essence, the computer "trains" on the training site and then locates pixels having similar signatures through a set of classification rules that have been programmed into the system. The pixels assigned to each land cover category are summarized statistically and displayed in a false color on the CRT. These results can then be photographed from the CRT or output on a printer or plotter for making map overlays. The results can also be written on magnetic tape for offsite processing or additional analysis on conventional computers. Figure II-4 is a schematic showing the flow of information when the Landsat Multispectrual Scanner is used as an aid for estimating parameters for hydrologic models. Either existing photography or limited underflights in light aircraft are necessary for defining the training sites needed for the computer to develop the land cover classifications. These aerial photos are also needed to define the specific characteristics of the various landcover categories that are needed by the hydrologic model. For example, both STORM and WREM require the percents of imperviousness associated with the various land cover types in order to simulate the runoff. These representative values are combined with the output from the interactive computer which shows the percent of the area assigned to each category to produce model estimates for the watershed.

C. Experiences with Landsat

Shortly after the 1972 launch of Landsat 1, scientists, engineers, agriculturists, hydrologists, and planners started reporting successful

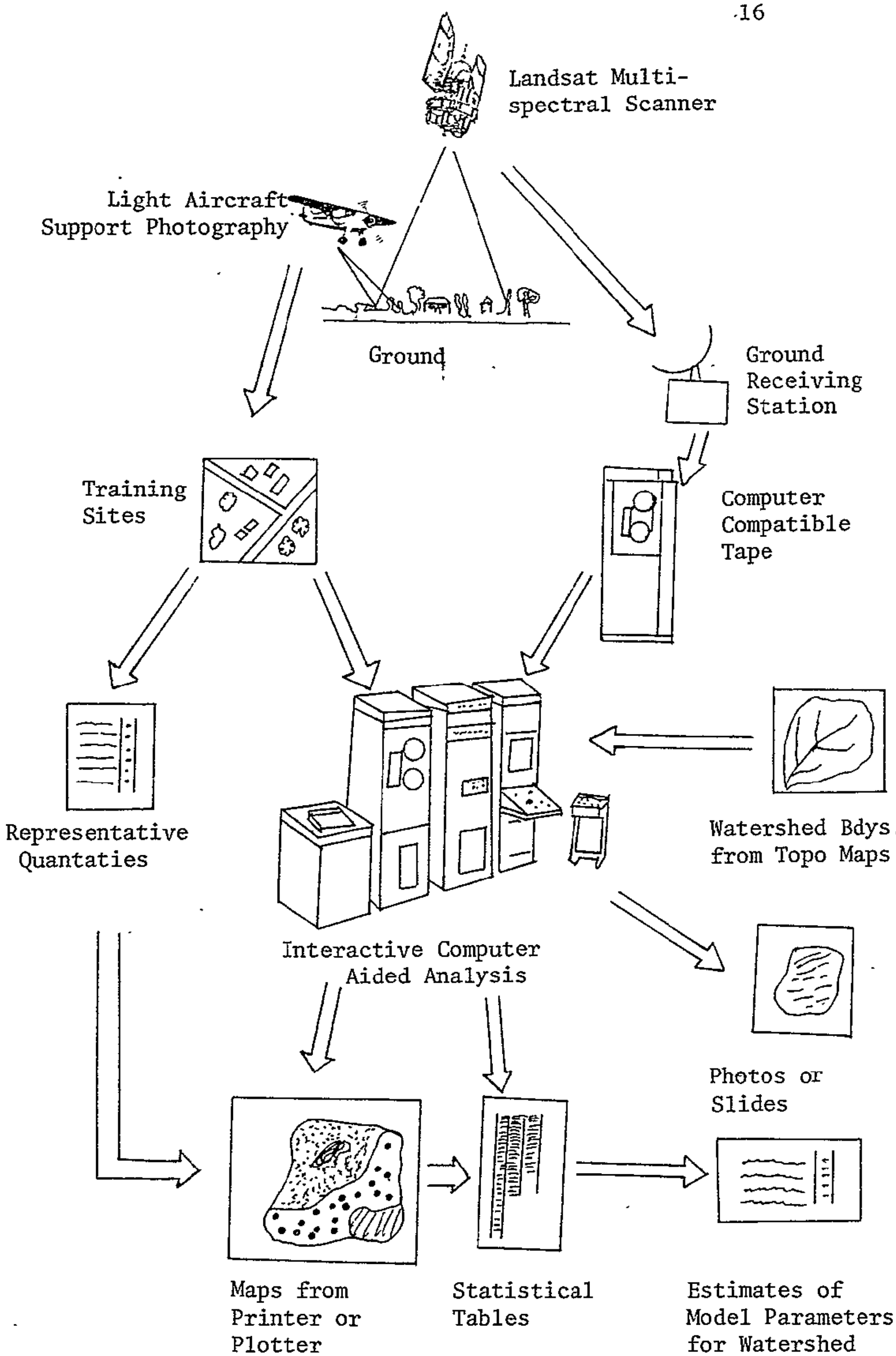


FIGURE II-4

Information Flow for Landsat-Based
Hydrologic Modeling

efforts in determining numerious land covers with the satellite data. Papers by Rango, McGinnis, Salomonson, and Wiesnet (1974), Rango (1975), and Rango, Foster, and Salomonson (1975) summarize much of the work in hydrology. Papers by Burgy and Algazi (1974), Blanchard (1975), and Solomonson, Ambaruch, Rango, and Ormsby (1975) are specifically concerned with the use of Landsat in hydrologic modeling. In a closely related field, determination of non-point sources of pollution as part of "208 Studies", a paper by Schecter (1976) provides an example of the "state-of-the-art" for management of model parameters for large areas.

Two experiments conducted by the University of Maryland led to the decision to undertake the Fourmile Run Study. The first was an inventory study on the 342 sq km (132 sq. mi) Maryland portion of the Anacostia River Basin, Ragan and Jackson (1975). A part of that study investigated the use of Landsat data for estimating the percent of imperviousness and the associated land covers needed for urban hydrologic modeling. The Landsat derived information compared favorably with similar data that had been developed through analysis of aerial photographs having a scale of 1:4800. For example, the overall watershed imperviousness was estimated as 25.1% and 23.5% with the Landsat and photographic approaches respectively. Table II-II compares estimates of the individual land cover categories developed with the Landsat and photographic approaches.

The agreement between the satellite and photographic approahces in the Anacostia Watershed was quite good. Approximately 94 man-days were required to complete the land cover analysis with aerial photographs while

TABLE II-II

PERCENT OF WATERSHED DEVOTED TO SEPCIFIED LAND USE
(Anacostia River Basin)

1	2	3
Land Use	Large Scale Aerial Photo	LANDSAT
Forested Areas	30.7	27.0
Highly Impervious	4.9*	6.5
Grassed Areas	8.5	10.4
Residential	44.9	43.5
Streets and Highways	9.9	5.5
Bare Land	N.C.	.4
Stream	1.0	N.C.
Pond or Pool	.1	N.C.
Unclassified Pixels	----	6.7

N.C - Not Classified

*Industrial-Commercial-Parking Lot

less than four man-days were required to accompolish similar tasks using the Landsat data. Although the economics and man-power requirements showed the Landsat approach to be extremely efficient, there were some questions that would have to be answered before the satellite approach could be recommended for "real world" hydrologic modeling. First, there was the question concerning the lower limit on the size of watershed that can be modeled. Table II-III from Ragan and Jackson (1975) showed that errors in the percent of imperviousness, a dominant parameter in the run-off process, increased significantly as the watershed size was decreased. The second question concerned the importance of differences in parameter estimates by two remote sensing systems relative to the sensitivity of the hydrologic model.

A reconnaissance type study directed toward the problems of size and different remote sensor types was then designed for a 54.6 sq. km (21.1 sq. mi) subwatershed draining into the Northwest Branch of the Anacostia River, a portion of the earlier study. In this study, reported in detail by Ragan and Jackson (1976), the Maryland National Capital Park and Planning Commission (MNCPPC) had used 1:4800 aerial photographs, detailed soil maps, and field surveys to define the input information required for the TR-20 version of the Soil Conservation Service (SCS) Model (1969). This particular version of the SCS Model is computer based and the input data requires extensive land cover information and channel cross-section. Detailed land covers defined by Table II-IV were used by MNCPPC to generate a synthetic flood frequency series for the 54.6 sq. km (21.1 sq. mi) subwatershed.

TABLE II-III

AGREEMENT BETWEEN ESTIMATES OF IMPERVIOUSNESS AS FUNCTION OF SUB-AREA SIZE

Size of Sub-Area sq. mi	sq. km.	Correlation Coefficient	Std. Error (% Imperviousness)
3.59	9.30	.93	5.29
2.29	5.93	.88	6.90
1.29	3.34	.88	7.20
.57	1.48	.83	8.33
.14	.36	.62	12.34

Table 2-2.--Runoff curve numbers for selected agricultural, suburban, and urban land use. (Antecedent moisture condition II, and $I_a = 0.2S$)

LAND USE DESCRIPTION	HYDROLOGIC SOIL GROUP			
	A	B	C	D
Cultivated land[1]: without conservation treatment	72	81	88	91
with conservation treatment	62	71	78	81
Pasture or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or Forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover[2]	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc				
good condition: grass cover on 75% or more of the area	39	61	74	80
fair condition: grass cover on 50% to 75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential [3]				
Average lot size — Average % Impervious[4]				
1/8 acre or less — 65	77	85	90	92
1/4 acre — 38	61	75	83	87
1/3 acre — 30	57	72	81	86
1/2 acre — 25	54	70	80	85
1 acre — 20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers[5]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

[1] For a more detailed description of agricultural land use curve numbers refer to National Engineering Handbook, Section 4, Hydrology, Chapter 9, Aug. 1972.

[2] Good cover is protected from grazing and litter and brush cover soil.

[3] Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

[4] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[5] In some warmer climates of the country a curve number of 95 may be used.

TABLE II-IV

Curve Numbers from SCS-TR-55

The University of Maryland organized two teams to develop synthetic flood frequency series for the same point on the stream as that used by MNCPPC. One team used digitized soil data and 1:24000 color infrared photographs to define the land covers shown by Table II-IV. The second team used the Image 100 and a general soil map to define the land covers shown in Table II-V. The two University teams then used a hand computation version of the SCS Model described in Chapter 24 of SCS NEH-4 (1972). Table II-VI compares the results of the three approaches.

The agreement amoung the three frequency series of Table II-VI is encouraging. Still, it is only one case and there is no streamflow data that can be used to determine if any of the three approaches are meaningful. There is a USGS gauge at the point on the stream where the computation were applied, but the long term record is not applicable because the present land cover developed during the late 1960's and early 1970's. Thus, the result of the experiment was that for one case, once the decision on the model had been made, the results obtained using relatively simple inputs were essentially the same as those produced by very complex inputs. The man-days involved in this study were approximately 160 for the MNCPPC approach, three for the color infrared approach, and less than one for the Landsat based modeling.

The results of the inventory study of the 342 sq. km (132 sq mi) Anacostia River Basin and the SCS model experiments on the 54.6 sq. km (21.1 sq. mi) subwatershed exposed the need for a much more comprehensive study in which Landsat and conventional input data impacts could be compared. The comparisons needed to be made in a "real world" situation where there was extensive ground truth, supporting hydrologic data, and

TABLE II-V

RUNOFF CURVE NUMBERS FOR LAND USES THAT CAN BE DEFINED FROM LANDSAT CCT ANALYSIS

Land Use Description	Hydrologic Soil Group A	B	C	D
Forest Land	25	55	70	77
Grassed Open Space	36	60	73	78
Highly Imperviousness (Commercial, Industrial, Large Parking Lot)*	90	93	94	95
Residential	60	74	83	87
Bare Ground	72	82	88	90

*Probably sufficient to use CN = 93 for all soils

TABLE II-VI

Discharges and River Stages Computed
With SCS Models

Randolph Road Gaging Station on
Northwest Branch of Anacostia River

Return Period (yrs)	Precip. (in)	Discharge (cfs) TR-20	Landsat	U-2	Depth of Flow (ft) TR-20	Landsat	U-2
2	3.0	2990	3490	3850	8.9	8.7	9.1
5	3.3	4610	5140	6064	10.0	9.4	9.6
10	5.4	6210	6900	7580	10.9	11.8	11.9
25	5.8	7390	8750	9300	11.7	12.3	12.7
50	6.7	9020	9900	10400	12.5	13.0	13.3
100	7.3	10,780	11,100	11,800	13.5	13.7	14.1

a mechanism for coverting differences in model outputs to economic consequences. It was at this point that the University of Maryland entered into an agreement with Water Resources Engineers, Inc. and NASA to test Landsat on the Fourmile Run Study that WRE was conducting for the Northern Virginia Planning District Commission.

CHAPTER III

SETTING FOR THE FOUR MILE RUN STUDY

A. Background

Four Mile Run is a heavily urbanized (50.5 sq. km.) watershed located in the Northern Virginia suburbs of Washington, D.C. The watershed has experienced frequent severe flooding with the seven largest floods occurring within the last thirteen years. The lower portions of the watershed have been most damaged by the flooding.

The mouth of Four Mile Run is located on the western shore of the Potomac River at the southern end of National Airport where the stream discharges beside the terminal facilities. Immediately upstream from its mouth, the stream passes beneath the George Washington Parkway bridge, the Richmond, Fredericksburg and Potomac Railroad yard culverts and the Jefferson Davis Highway bridge (Route 1). Continuing upstream the creek forms the boundary between the City of Alexandria and Arlington County until it reaches Interstate 95, the Shirley Memorial Highway. After briefly entering a corner of Alexandria, the stream turns northwestward, enters Arlington and roughly parallels the Arlington County-Fairfax County boundary until it enters the City of Falls Church. The stream becomes intermittent in Falls Church although it actually has its beginnings in the Brilyn Park area of Fairfax County. A watershed map for Four Mile Run is shown in Figure III-1. Table III-I summarizes the physical characteristics of Four Mile Run and its tributaries. All the tributaries have steep slopes and can generally be classed as having rapid and very peaked runoff characteristics.

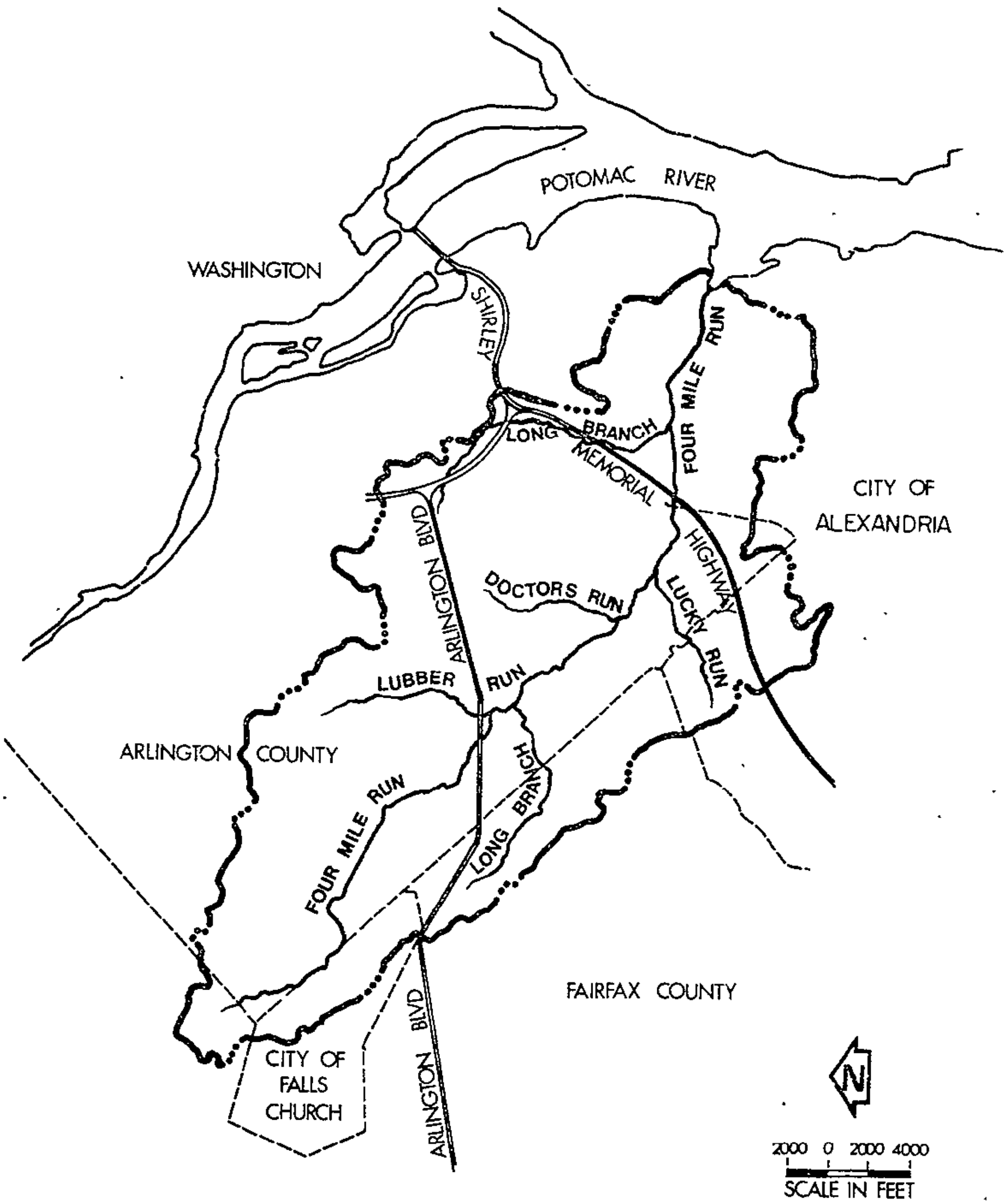


FIGURE III-1

Four Mile Run Watershed Map

(from WRE (1975))

TABLE III-I

Physical Dimensions of Four Mile Run and Its Principal Tributaries

Name of Stream	Drainage Area (sq. Mi)	Length (mi)	Slope (ft/mi)
Lubber Run	1.6	2.3	79
Long Branch (Upper)	1.0	2.5	80
Doctors Run	1.4	2.0	89
Lucky Run	1.3	1.3	117
Long Branch (Lower)	2.5	3.3	67
Four Mile Run Total	19.5	9.3	45

The transportation network of roads and railroads serving the Washington metropolitan area from the south developed in the early nineteen hundreds. Route 1 was the principal highway and the Richmond, Fredericksburg and Potomac Railroad yards provided the railroad link. Both arteries lie close to the western bank of the Potomac River as they pass through northern Alexandria and southern Arlington before entering the District of Columbia along the 14th Street corridor. Along this route both transportation links cross the mouth of Four Mile Run. The rail yard culverts and the Route 1 bridge were designed and in place in a low-lying flood plain long before the suburban expansion of the Arlington-Alexandria area occurred. The later construction of the George Washington Parkway and its bridge

added to the problems of flow constriction. It was the post World War II period that nurtured urban transition in the Washington Metropolitan Area which resulted in the entire Four Mile Run watershed being urbanized. The urban area grew to include the portions of Fairfax County and the City of Falls Church which form the upper part of the watershed.

The urban transformation has resulted in a hydrologic change in the watershed. The most obvious change is in the runoff characteristics, since six of the seven largest peak discharges have been recorded since 1966. The second largest flow was in 1963.

The Arlandria area, lying between Arlington and Alexandria, is the most vulnerable urbanized area in the Four Mile Run flood plain. It has been inundated regularly, with the highest stage resulting from Hurricane Eloise in 1975. The U. S. Army Corps of Engineers, Baltimore District, (1972) analyzed the flooding events and suggested that the channel conditions and the bridge/culvert openings near the mouth were dual causes for the flooding. Consequently, they recommended channel improvements and expansion of bridge culvert openings. That recommendation was approved by the U.S. Congress as part of PL 93-251. However, the effect of urbanization was noted by the authors of the law and it contained a requirement that the local jurisdictions develop a program to analyze future proposed land use changes in view of their potential for increasing flooding. The flood improvements were not to be jeopardized by future land use changes. The local jurisdictions agreed to participate in developing that program.

B. Mission of Water Resources Engineers

In September 1973, the Northern Virginia Planning District Commission, acting on behalf of four of its member units (the Cities of Alexandria and Falls Church and the Counties of Arlington and Fairfax), selected Water Resources Engineers to conduct a study of the relationship between urban development and flooding for the Four Mile Run Basin. The study was in response to the enabling legislation which authorized a Flood Protection Project by the USACE to modify the lower Four Mile Run channel with the corollary requirement, as mentioned earlier, that the local governments having jurisdiction within the Basin undertake a land use study to insure that future land use changes will not jeopardize the Flood Protection Project.

The study program was to accomplish the following objectives:

1. Estimate the contributions of runoff from each jurisdiction to large flows under current conditions,

2. Evaluate the effectiveness of runoff control measures, and

3. Establish a cooperative program through which each local government unit may use the same procedure to evaluate individual land use changes and runoff control measures.

As indicated by the objectives listed above, there were many elements of the WRE-NVPDC efforts associated with the Four Mile Run Study. The present report considers only the hydrologic modelling aspects.

WRE decided to use two hydrologic models to meet the objectives of the study. The models were: 1) STORM developed by the USACE(1972);

and 2) the WRE Runoff Model(WREM) which is an outgrowth of the EPA Storm Water Management Model(1972). The models are complementary to each other. STORM is a relatively simple model which is easy to apply, inexpensive to run, and is intended as a preliminary planning or screening tool. WRE used STORM to evaluate the rainfall-runoff relationship for the basin. STORM accepts long term rainfall records and produces the resulting series of runoff events. In the approach used by WRE, STORM was calibrated for present land use conditions by fitting the flows predicted by the model for several recent major storms to those measured by the U. S. Geological Survey (USGS) at the Alexandria stream gage.

Using the historical meterologic data the calibrated model was used to generate peak annual flows from the hourly rainfall record from 1922 to 1973. This 52-year series of peak annual flows was then used to develop a flow-frequency relationship for the Basin which, when coupled with available stage-discharge and stage-damage curves, allows "planning level" evaluations of the annual economic losses associated with alternative flood control approaches to be made. STORM also allowed WRE to select those characteristics of real storms which impacted most significantly on the watershed. This information was used to develop the structure of a "Design Storm" to be used with WREM for the detailed hydrologic studies associated with subsequent phases of the Four Mile Run Study. Details on the use of STORM, its calibration, and the hydrologic and meterological data available has been described by WRE(1975).

The second model, WREM, is highly complex, performing a very rigourous mathematical analysis of flow from the onset of rain on the surface, through overland flow and concentration of flow in gutters and

small conduits, to final routing through sewers and open channels, to its ultimate disposition in the receiving waters. One phase of the continuing study involves the utilization of a design storm and WREM to ascertain design hydrographs under current conditions which are attributable to each jurisdiction.

Still another phase of the study will involve the selection of up to six typical areas within the watershed and use of these areas as the prototypes for evaluation of selected runoff control methods. A literature review of appropriate methods will be undertaken. WREM will then be used to evaluate the effectiveness of each method for localized and watershed runoff control.

C. Role of the University of Maryland

As outlined above, WRE used the best available land cover and streamflow data to calibrate STORM so that it would provide the best possible representation of the hydrology of Four Mile Run. In subsequent sections, this will be termed the "conventional version of STORM". As a parallel study, the University of Maryland provided WRE with land cover distributions and related model coefficients developed from computer aided analysis of Landsat MSS data. This provided WRE with what will subsequently be referred to as "a Landsat version of STORM" which had been developed as if Four Mile Run were an ungaged watershed. By operating the two versions of STORM in parallel the impact of using Landsat as opposed to conventional input data could be evaluated. The function of the parallel operation was to compare differences between: 1) the observed peak discharges used

for calibration by WRE and these estimated by the models; 2) the synthetic flood frequency curves; and 3) the predicted annual damages associated with alternative flood control techniques being considered at the planning level.

Because the above objectives were met well ahead of schedule, Landsat data was also supplied for a 179 subwatershed version of WREM. The selected design storm was input to the conventional and Landsat based versions of WREM to allow comparision of design hydrographs at various locations within Four Mile Run.

In so far as running the models was concerned, the University of Maryland simply functioned as a supplier of Landsat based coefficients. The models were then run by WRE on their system under the same conditions required to meet their responsibilities to NVPDC.

D. HYDROLOGICAL DATA BASE

Too often, the interpretation of hydrologic modeling results are seriously constrained by limited hydrologic data. Without good field data it is difficult to verify the calibration of the model, therefore, one must exercise extreme care in interpretating the significance of small differences in the model outputs. The hydrologic response of a watershed to a rainfall event is a complex phenomenon. Proper modeling requires that the distribution of rainfall be described both in time and space. It is also necessary that the resultant runoff be measured coincidently with the rainfall events, and evaporation and base flow should be described by pertinent data. The Four Mile Run Watershed was especially attractive for the present study because of the extent and quality of the hydrologic data base.

<u>D.1 Historical Rainfall Data</u> - WRE (1975) used historical rainfall records from sixty raingages to evaluate the precipitation distributions on Four Mile Run. The location of these gages is shown in Figure III-2 where the numbers refer to a table in the WRE (1975) report that describes the type, exact location, period of record, etc. of each gage. All gages were not operative during all periods of rainfall analyzed. Because only recent storms occuring on the current land cover of the watershed were used for calibration, the raingage coverage was extensive for each event. The focal point of the rainfall inputs to STORM was the National Weather Service gage at National Airport. This gage has been at its present location at National Airport since 1941. Prior to 1941 it was located in Washington, D.C., approximately 3.5 miles north of its present location. Records for the gage have been published as hourly totals for the period 1922 to the present.

The purpose of the analysis of rainfall distribution by WRE was three-fold. First, any significant long term trend in the major storm events had to be identified. Second, the persistent type of storm which creates major flooding events had to be identified, and third, reliable isohytel patterns for the major storm events for use in the model calibration had to be defined. These results indicated that the peak one-hour intensities (greater than two inches per hour) occur during thunderstorms and that the largest total rainfall occurs during storms caused by hurricanes and tropical storms. The results also show that the July 22, 1969, storm had the largest one-hour rainfall intensity since 1922.

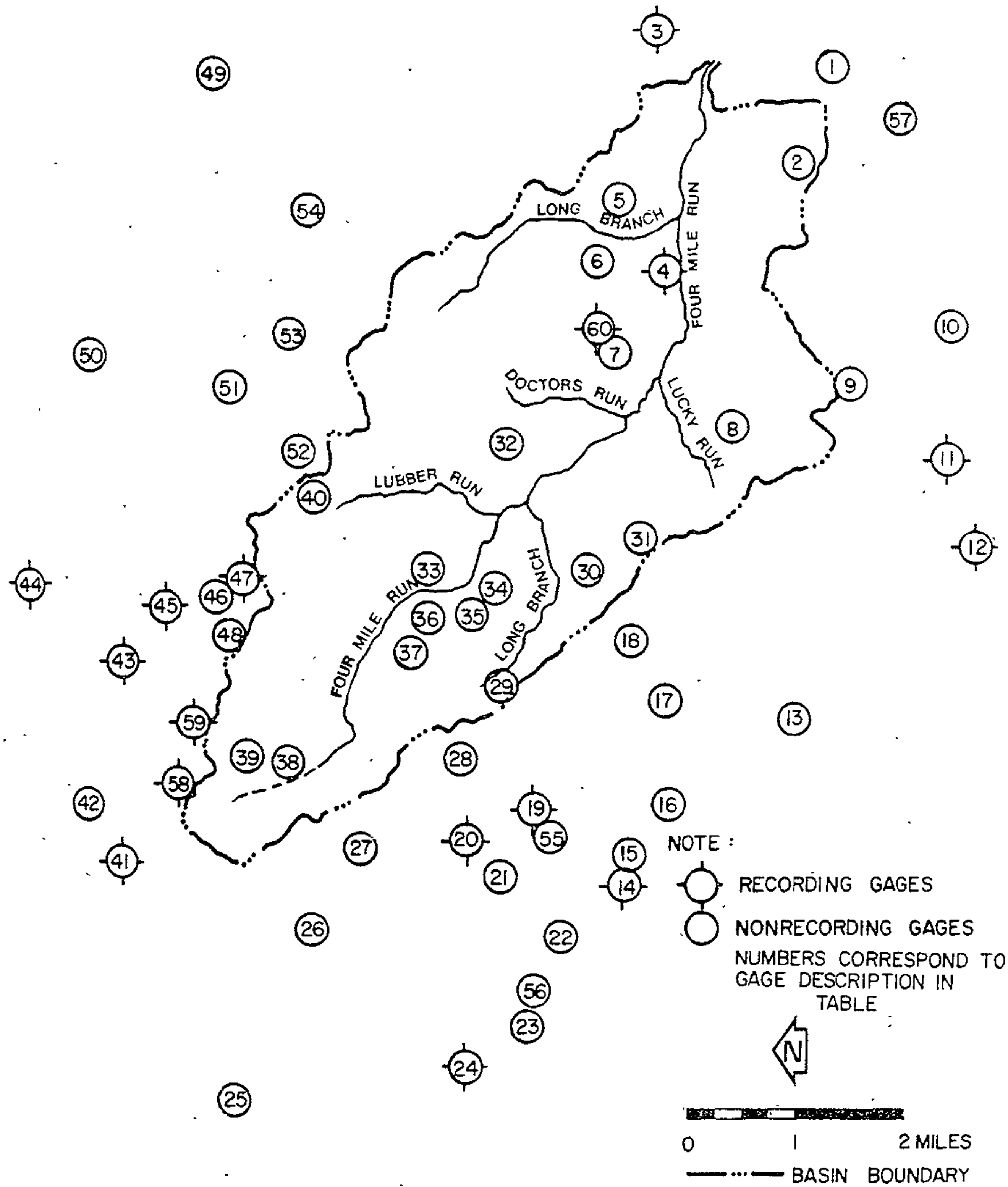


FIGURE III-2

Recording and Nonrecording
Rainfall Gages near Four Mile Run
(From WRE (1975))

The history of storms with a peak one hour intensity greater than 1.0 inches per hour was examined to identify any seasonal variation. A total of 78 such storms have occurred since 1922. There is a clear seasonal trend with all these large storms occurring in summer or fall. None have occurred during the winter or spring season. Thus the effects of freezing and snowmelt were not considered in the study.

The areal distribution of rainfall in the Four Mile Run Basin was determined for each of the storms to be used in the calibration of the hydrologic models using the entire network of available recording and nonrecording rainfall stations. Shown in Figures III-3 and III-4 are the example isohyetal maps for two of the storms. The large variations in the rainfall patterns from one storm to the next is surprising because of the relatively small size of the watershed.

As described in detail by WRE (1975), temporal and average basin rainfall correlations with the National Airport recording gage were made so that only one magnetic tape record would have to be used as the input to STORM when it was operated as a continuous streamflow simulator. Figure III-5 shows ratio of total Annual Precipitation in the basin to that at National Airport for the period of record. This led WRE to decide that when STORM was operated as a continuous streamflow simulator, the average basin precipitation would be represented as 1.055 times the hourly percipitation read from the magnetic tape of the National Airport gage. It should be emphasized that the actual isohyetals for the individual storms, rather than the 1.055 coefficient, were used during the calibration of STORM.

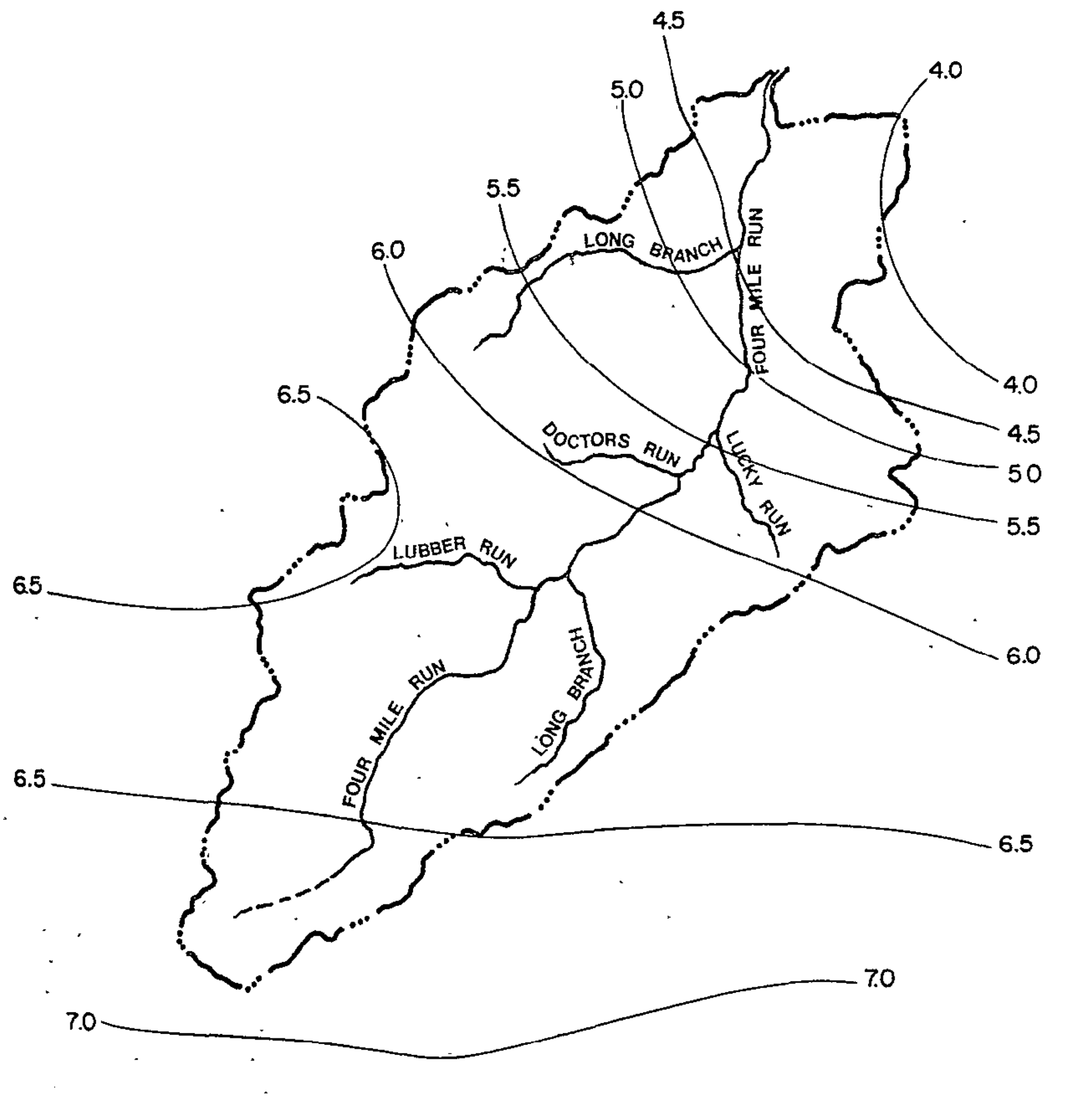


FIGURE III-3

Areal Distribution of Total Rainfall
for September 13-15, 1966
(from WRE (1975))

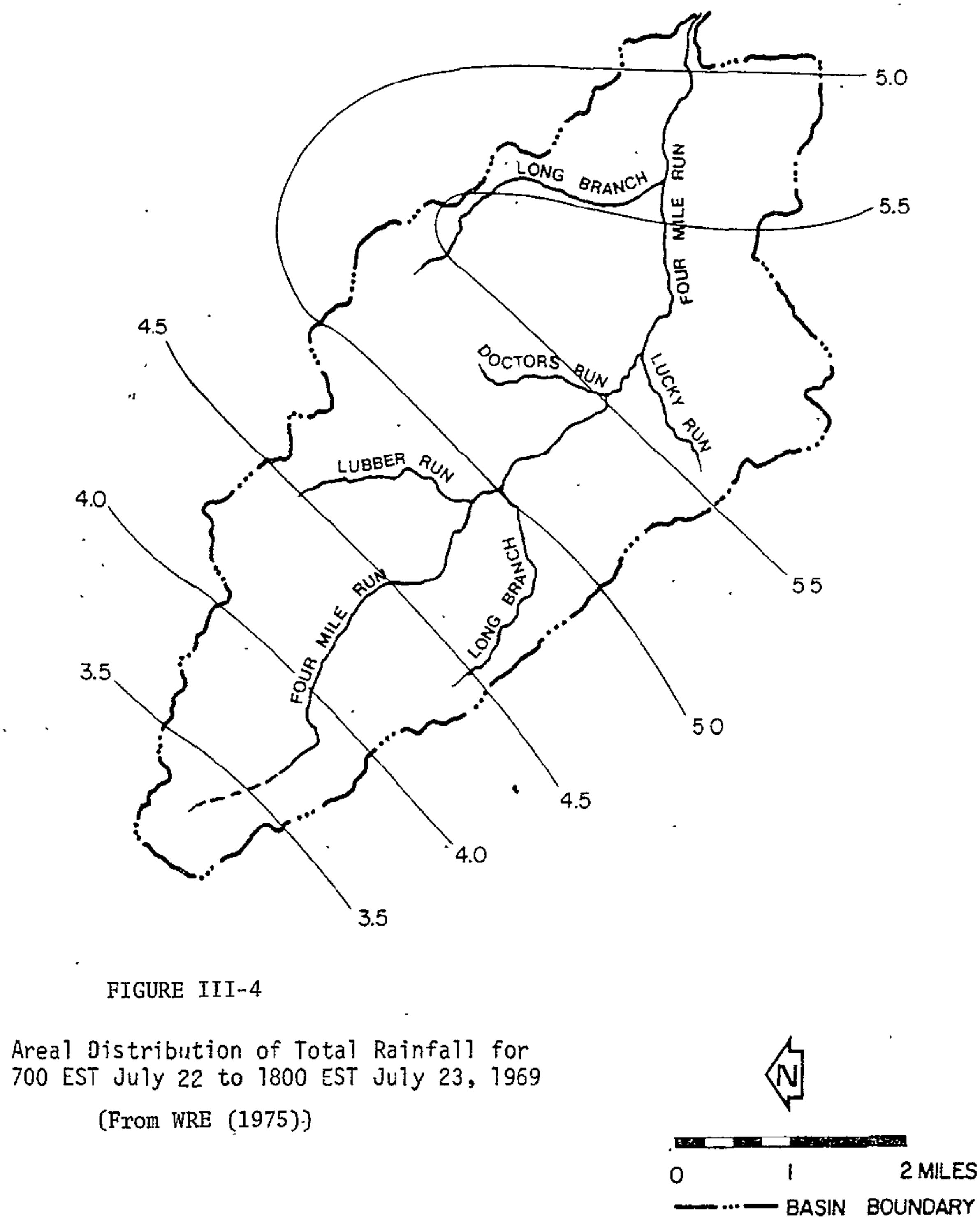


FIGURE III-4

Areal Distribution of Total Rainfall for 700 EST July 22 to 1800 EST July 23, 1969

(From WRE (1975))

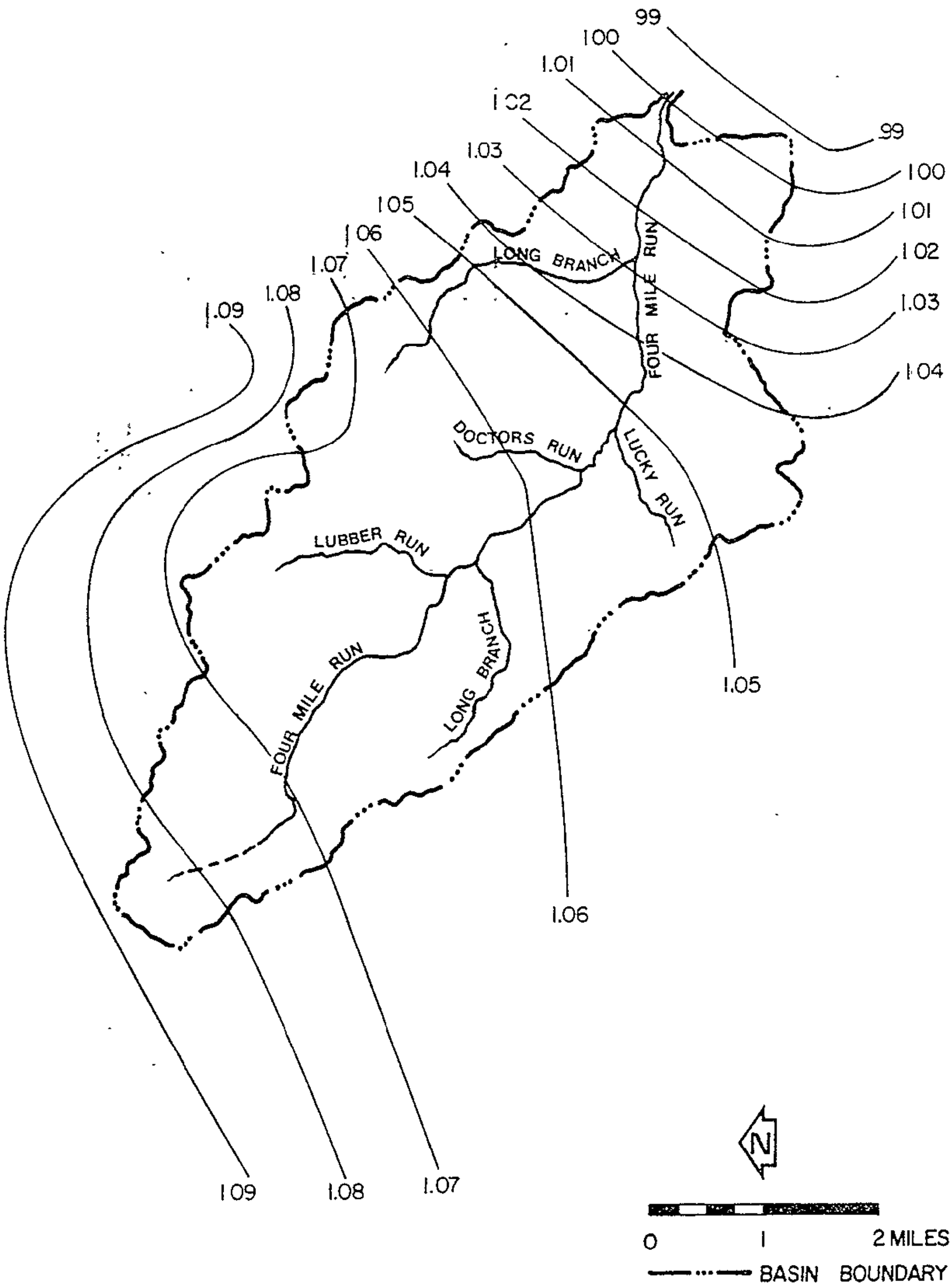
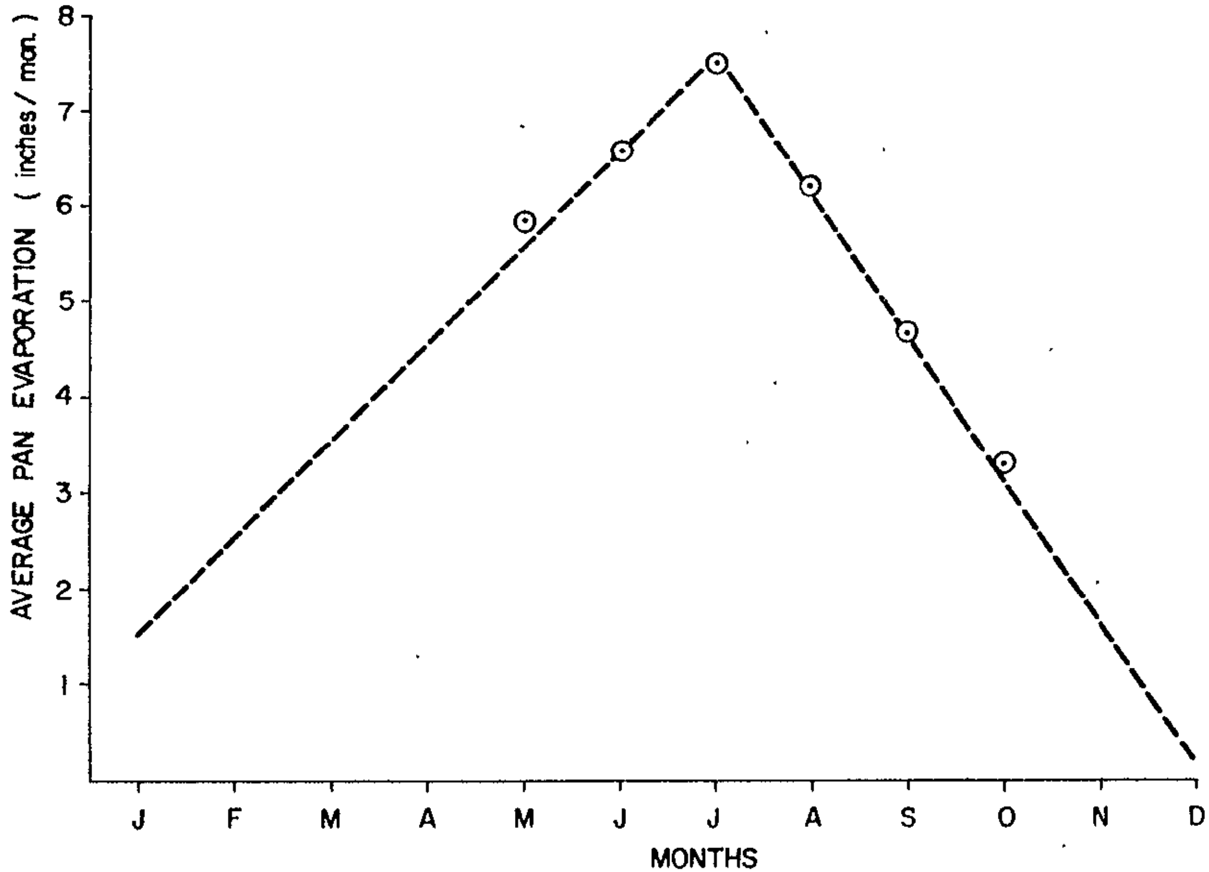


FIGURE III-5

Ratios of Total Annual Precipitation
in the Basin to that at National Airport
for NWS Period of Record
(From WRE (1975))

D.2 Evaporation Rates - Evaporation directly affects the available depression storage in the Basin. Thus, the evaporation that occurs before a storm affects how much of the rainfall will occur as runoff from the Basin. The pan evaporation rates were judged by WRE (1975) representative of the evaporation process for the storage depressions considered in STORM. Therefore, average monthly pan evaporation rates were determined as illustrated in Figure III-6. The NWS estimate of the pan coefficient for the area is 0.76 (1974). Due to frost interference, pan evaporation measurements were made only for the months of May through October. Based on NWS estimates of total yearly evaporation the measured variation from May to October was extrapolated in order to estimate the variation in pan evaporation for the entire year.

D.3 Base Flow - Base flow, which consists primarily of groundwater discharge during dry weather, is the portion of stream flow excluding direct runoff. During and immediately after rainfall events there is a second component of base flow. This component is a result of rainfall that reaches the stream as interflow (subsurface flow of water in upper soil layers). Examination of the daily average runoff records by WRE (1975) indicated that dry weather flow is reached within one day after the end of major rainfall events. Thus, the interflow component of base flow is significant for less than a one-day period after the end of a rainfall event. The Basin has a very short response time to direct runoff. The response time of interflow is significantly longer; consequently interflow was judged to be an insignificant component of peak discharge for flooding events with a recurrence interval greater than two years. During periods



NOTE · ⊙ Measurements made at Beltsville, Maryland by NWS - Average over 29 years of record

FIGURE III-6

Average Monthly Pan Evaporation Rates
for Washington, D.C. Area
(From WRE (1975))

without rainfall the average daily stream flow of Four Mile Run varies between 3 and 7 cfs. This is the dry weather base flow. This ground water discharge component of streamflow is insignificant relative to peak discharge rates for flooding events with a recurrence interval greater than two years, and was not included in flood flow analyses.

D.4 Historical Streamflow Data - Historical streamflow records are available from the USGS for several gaging stations within the Four Mile Run Basin, shown in Figure III-7. The period of record and type of gage varies between gaging station locations. Streamflow data were organized by WRE (1975) for use in the model calibration and to aid in determining the effects of urbanizations on the Basin.

The Alexandria Four Mile Run gaging station, located 1.8 miles upstream from the mouth, has yielded a continuous record of stage from 1951 to 1969. This gaging station was destroyed in the July 1969 flood and was replaced with a temporary peak stage recorder at the same location in September 1969. The data from the peak stage recorder was destroyed in the flood of June 1972. A permanent gaging station located 2000 feet upstream from the original gage went into operation in October 1973. Peak discharges during periods when there was no gage in operation were estimated using high water marks. This Alexandria gage was used for the calibration of STORM described in Chapters IV and V. The drainage area above this point is 37 sq. km (14.3 sq. mi).

E. Economic Data Base

Extensive field surveys and economic studies preceeded the decision to construct the USACE flood control project on Four Mile Run. The

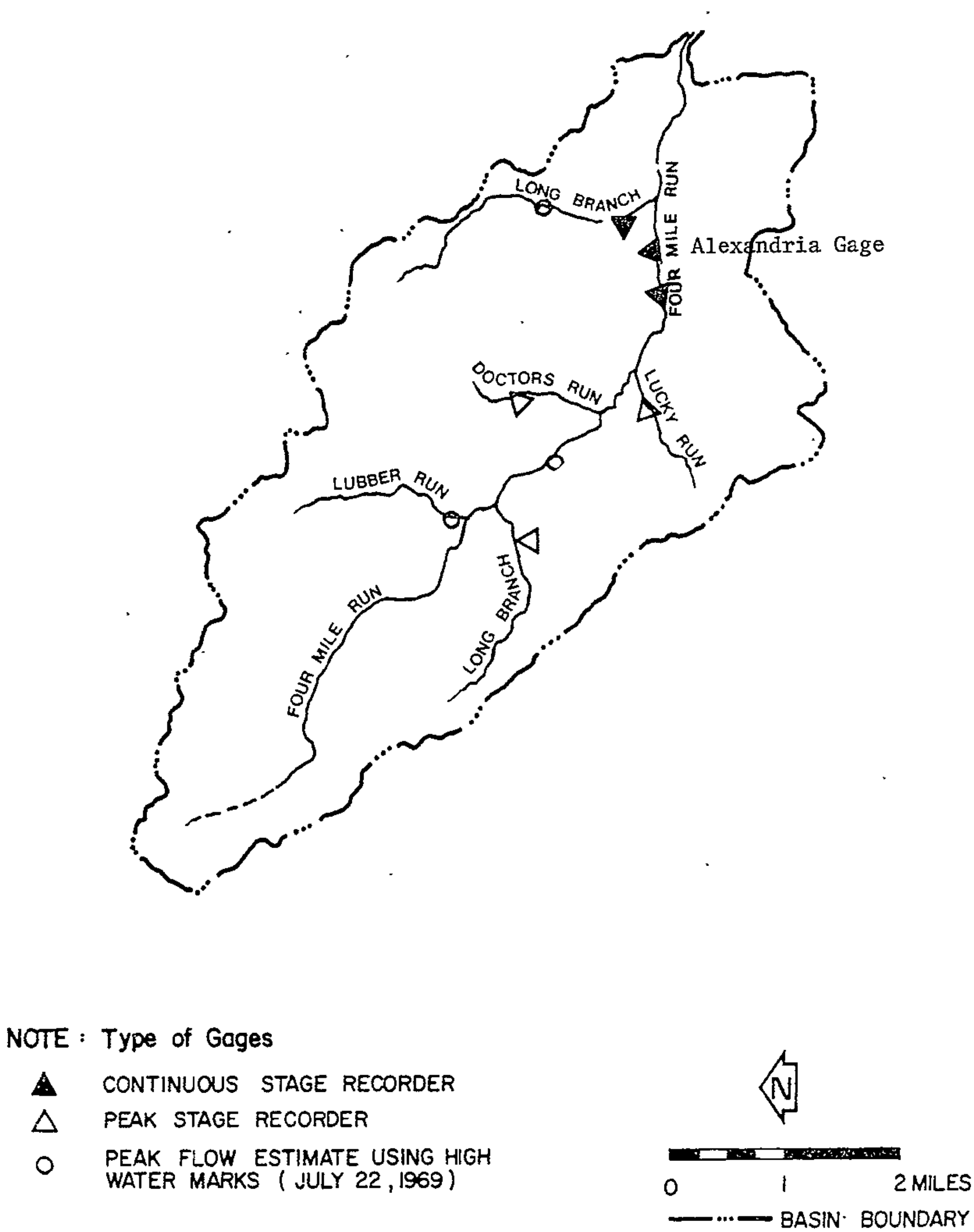


FIGURE III-7

USGS Stream Gage Locations
in Four Mile Run Watershed

(From WRE (1975))

availability of excellent stage-discharge and stage-damage data would allow differences between the discharges computed by the conventional and Landsat versions of STORM to be evaluated in terms of economic damages. The discharge-damage curves derived from USACE data developed for the natural and improved channel conditions are presented as Figure III-8.

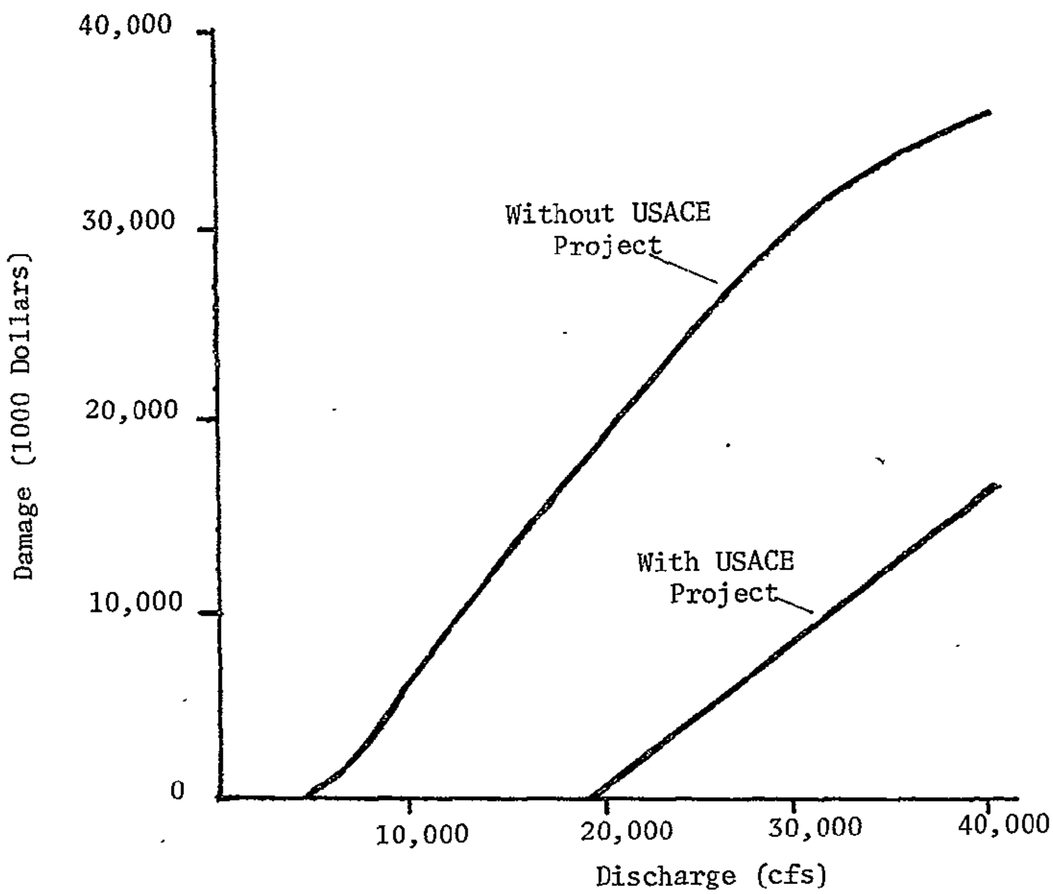


FIGURE III-8

Discharge-Damage Curves for Four Mile Run at the Alexandria Gage

CHAPTER IV
CONVENTIONAL APPROACH USED TO DETERMINE LAND COVER AND CALIBRATE STORM

In order to produce an accurate determination of the runoff conditions in Four Mile Run, the hydrologic model STORM was used to evaluate the rainfall-runoff relationship. STORM is a continuous simulation model capable of representing the effects of the temporal distribution of rainfall for an entire period of record. Because it is inexpensive to run it can be used with several decades of rainfall data to yield a complete flow frequency analysis. For a comprehensive description of STORM the reader is referred to WRE (1975).

STORM represents the rainfall-runoff phenomenon by the general expression:

$$Q = C(P-f)A \qquad \text{(IV-1)}$$

where Q = stormwater runoff rate from the Basin (acre-inches/hr),

C = composite runoff coefficient representing losses due to infiltration (dependent on land use),

P = average rainfall rate over the Basin (in/hr),

A = total watershed area (acre),

f = available depression storage (in/hr),

$$= \frac{f_o + N_d E}{D_t}, \quad f < f_{max}$$

f_o = available depression storage after previous rainfall (in),

N_d = number of dry days since previous rainfall (day),

E = evaporation rate (in/day),

f_{max} = maximum available depression storage (in) and,

D_t = time increment (hr).

These expressions are computed continuously to yield a discharge hydrograph from the watershed without routing the flow through the stream system.

The model was calibrated by WRE as will be discussed in the following sections, using recent hydrologic records (1963-1972) and present land use characteristics. Once calibrated, the model was used with historical precipitation records (1922-1973) to predict the runoff that past storm events would cause under present land use conditions. This model analysis was used to determine the relationship between flood magnitude and recurrence intervals. The results of this analysis were also used to select the characteristics (intensity and duration) of real storms which cause the most significant impact on the Basin. This information proved useful in identifying the characteristics of the required design storm.

As will be illustrated in this chapter, the model STORM is not capable of simulating the entire range of possible flood events with a single set of model parameters. Since this study is concerned with the development of discharge hydrographs for major storm events, the model was calibrated for flow events with a recurrence interval greater than five years.

A. *MODEL CALIBRATION*

The six storm events listed in Table IV-1 were chosen for use in model calibration. These storms were selected based on flood magnitude, recentness of occurrence, and availability of rainfall and runoff data. These storms were used in conjunction with present land use classifications

TABLE IV-I. Calibration Storms

Rank No. (1971-1972) (Measured Flow)	Calibration Storms Date	Calibration Storms Basin Rainfall (in)	USGS Estimated Peak Flow (cfs)	Complete Hydrograph Available?
2	Aug. 19-20, 1963	2.49	11,700	Yes
6	Sept. 13-15, 1966	5.76	6,900	Yes
1	July 22, 1969	4.02	14,600	No
5	Aug. 2, 1969	1.90	8,300	No
4	July 9, 1970	4.92	8,800	No
3	June 21-22, 1972	8.03	10,000	No

as a basis for adjusting the runoff coefficients used in STORM until the model effectively reproduced field conditions. The result of this task was a calibrated simulation model that can be used to generate extended runoff records from the long term rainfall records at National Airport.

The reliability of the model in simulating past storm events under present conditions was verified by refining STORM until recent storm events were accurately simulated. Briefly the calibration process consisted of the following procedures:

1. Select several storms for which:
    a. Representative Basin rainfall may be determined,
    b. Runoff hydrographs are available, and
    c. Land use characteristics are known.
2. Describe physical characteristics of the watershed land use classifications and impervious areas.
3. Estimate values for the runoff coefficients and depression storage.
4. Run the model for each of the storms (including at least two weeks prior to each storm) and compare the resulting discharge hydrographs with the measured hydrographs.
5. Alter the runoff coefficients and possibly the percentages of imperviousness (to account for impervious areas not directly connected to the storm sewer systems).
6. Repeat steps 4 and 5 until the model results are representatives of measured discharges.

Model calibration is an iterative process of selecting model parameters, using the model to predict runoff and comparing model predictions to observed hydrographs. All calibrations are considered simultaneously. The process is complete when predictions closely approximate all hydrographs. As stated earlier the STORM does not route channel flow or account for variation of rainfall over the Basin. Therefore, the spatial variation of rainfall and channel storage are not considered in this phase of the study. The average basin rainfall pattern was determined for each of the calibration storms as described in Chapter III. Channel storage and spatial distributions of rainfall were considered in the detailed analysis using WREM.

A description of the rainfall and runoff data used for calibration storms has been presented in Chapter III. Based on past experience approximately five calibration storms should be analyzed to verify the model. Average Basin rainfall was calculated for the six largest floods. A seventh storm (20 July 1969) which occurred two days prior to the flow record (22 July 1969) was also studied. This smaller storm was used to study the effect of antecedent moisture conditions and to check the validity of the calibrated model for minor floods.

The reason for selecting these storms is that they generate the six largest flood flows. Ideally, land use data should be available in order to define the actual runoff coefficients based on land use at the time of each storm's occurrence; however, since such land use data were lacking, the analysis was made with the best available land use data from the recent NVPDC update for the four watershed jurisdictions. This update was completed in January 1975.

B. DEVELOPMENT OF LAND USE AND PERCENT OF IMPERVIOUSNESS

A necessary input to the hydrologic models is a description of the physical conditions of the basin. This information includes data on percentages of impervious area associated with each land use classification, runoff coefficients (or infiltration capacity) of the impervious and pervious areas, and depression storage. Each of these parameters is described in the following sections.

B.1 *Existing Land Use Patterns*

An existing land use map at a scale of 1" = 1000' was prepared by the NVPDC staff for use in calibration of the hydrologic computer model. Since only one of the four watershed jurisdictions possessed an updated existing land use map, aerial photographs were used to convert future land use plans to existing land use maps for the other three jurisdictions. Frequent site inspections were required to resolve cases where aerial photos did not provide sufficient detail.

After the local future land use plans had been converted into existing land use maps, watershed land areas were correlated with one of the following land use categories:

Low Density Residential (0-8 DU/Acre)

Medium Density Residential (9-13 DU/Acre)

High Density Residential (14-55 DU/Acre)

Commercial-Office

Industrial

Government-Institutional (excluding schools)

Schools

Vacant

The densities assigned to residential land use classifications vary considerably from one watershed jurisdiction to the next. Through an analysis of impervious area percentages associated with Four Mile Run residential developments, the NVPDC staff determined that, on the average, residential clusters with densities in the range 9-13 DU/Acre had similar impervious area percentages. Impervious percentages increased rather noticeably for residential sample areas with densities of 14 DU/Acre and greater; conversely, impervious percentages for sample areas less than 9 DU/Acre were generally lower than those for 9-13 DU/Acre range. Based upon the results of this analysis, densities ranging from 0-8 DU/Acre as classified as *low density* and densities ranging from 14-55 DU/Acre as *high density*. The intermediate 9-13 DU/Acre range was designated as *medium density*. This composite classification system resulted in the distribution of residential land uses shown in Table IV-II.

The approach differs from traditional land use classifications in that it focuses on impervious ground cover, not the property ownership pattern. The former gives some indication of a land area's response to precipitation, whereas the latter does not. The methodology for map preparation relied heavily on the following *rules of thumb:*

1. Large-lot single family areas were subdivided into smaller pieces that conformed to the zoning for the property. Structures on the lot were assigned to one or more of the smaller pieces which were then denoted on the land use map as a *single family* use. Since the remaining pieces contained no impervious cover, they were assigned a vacant notation on the land use map. (Example: A one acre parcel with one dwelling unit and a zoning of 7 DU/Acre would have one dwelling unit with 6233 square feet (43,560/7) assigned to the low density category and 6 areas, each 6233 square feet in size, assigned to the vacant category).

2. Large wooded tracts and open field that do not appear to be important components of surrounding or adjoining urban land uses (residential, commercial-office, or industrial) were denoted as vacant on the land use map.

TABLE IV-II

Distribution of Residential Land Uses

By NVPDC Composite Classification System

Jurisdiction	Local Land Use Map or Plan Classification	Four Mile Run Watershed Classification
Arlington (Source: "General Land Use Plan," Office of Planning, Amendments through December, 1965)	Low (0-8 DUA) Low Medium (9-13 DUA) High Medium (>13 DUA)	Low Density Res. Medium Density Res. High Density Res.
Alexandria (Source: "Existing Land Use Plan Map" & "Long Range Land Use Plan Map," Revised February, 1974)	Res. Low (0-25 DUA) Res. Med. (26-45 DUA) Res. High (>45 DUA)	Low Density Res. and Medium Density Res. High Density Res. High Density Res.
Falls Church (Source: "Master Plan", Dept. of Planning Amended through April, 1973).	Low Density SF (0-3 DUA) Med. Dens. SF (3-5 DUA) Townhouse General Residential P.U.D.	Low Density Res. Low Density Res. Medium Density Res. High Density Res. High Density Res.
Fairfax (Source: Unpublished OCP Existing Land Use Maps, 1974)	Single Family Detached Townhouse Garden Apartments Elevator Apartments P.U.D.	Low Density Res. Medium Density Res. High Density Res. High Density Res. High Density Res.

3. Wooded areas and open fields over 200 feet in width that abut on Four Mile Run and its tributaries were denoted as vacant on the land use map even though some were attached to residential, commerical-office, and institutional land uses.

Table IV-III presents a breakdown of land use by jurisdiction as determined by planimetering this existing land use map. Figure IV-I is a photo reduction of the land use map developed by NVPDC for the study. A total of eight categories were used. Topographic maps of the sewershed were used to delineate the land areas tributary to the Alexandria stream gage (in use prior to 1970) and the Shirlington stream gage (in use after 1972). This subarea breakdown was needed for the STORM calibration.

The eight subcategories presented in Table IV-III were aggregated into five classifications for the STORM calibration runs. The area tributary to the Alexandria stream gage was subdivided into the following five categories: 1) low density residential, 2) high density residential, 3) commercial, office and institutional, 4) industrial and 5) vacant. Since the impervious area percentages associated with schools were similar to the lot coverage characteristics of low density residential land uses (see Table IV-V), school property was included in the low density residential classification. Impervious area considerations included the distribution of medium density residential land uses among the low density and high density residential classifications. The totals used for calibration of the model STORM are given in Table IV-IV.

B.2 *Impervious Area*

The amount of impervious area within each land use classification is necessary to determine the overall runoff coefficient for STORM, in equation IV-I.

CATEGORY	ALEXANDRIA*	ARLINGTON*	FAIRFAX	FALLS CHURCH	TOTAL*
LOW DENSITY RESIDENTIAL (0-8 DU/ACRE)	.5526 1/ /.1610/.1612 1/	5.622/4.[illegible]22/4.356	.7986	.4366 1/	7.4098/5.6182/5.7525
MEDIUM DENSITY RESIDENTIAL: (9-13 DU/ACRE)	.5761 2/ /0 3/ /.1062 4/	.389/.22[illegible]/.3349	.0258 1/	.009 2/	.9999/.2638/.4759
HIGH DESNTIY RECIDENTIAL (14-55 DU/ACRE)	.5637 5/ /.356 6/ /.3816 7/	1.833/1.[illegible]857/1.3085	.3323 2/	.0390 3/	2.758/1.997/2.0514
COMMERCIAL-OFFICE	.2308/.0738/.0739	.819/.388/.4445	.416	.029	1.4948/.9068/.9634
INDUSTRIAL	.2776/.0178/0179	.247/.089/.1129	0	.071	.5956/.1778/.2018
INSTITUTIONAL (excluding schools)	.1194/.0694/.0967	1.0005/.921/9605	.0921	.062	1.2785/ 1.1445/1.2111
SCHOOLS	.1455/.1083/.1083	.445/.3195/.3234	.002	.0147	.6072/.4445/.4484
VACANT	.5674/.4261/4261	3.3444/2.2244/2.3193	.4102	.018	4.36/3.0987/3.1936
TOTAL	3.0331/1.2064/1.3719	13.7044/9.6786/10.1601	2.087	.6793	19.5038/13.6513/14.2983

1/Does not include .2117 mi.^{2} of "R.Low" units @ 9-13 DU/ACRE

2/Includes .2117 mi.^{2} of "R.Low" units @ 9-13 DU/ACRE and does not include .4742 mi.^{2} of R.Medium @ densities greater than 13 DU/ACRE

3/Does not include .2934 mi.^{2} of "R.Medium" at densities greater than 13 DU/ACRE

4/Does not include .2934 mi.^{2} of "R.Medium @ densities greater than 13 DU/ACRE

5/Includes .4742 mi.^{2} of "R.Medium" @ 13 DU/A

6/Includes .2934 mi.^{2} of "R.Medium" @ 13 DU/A

7/Includes .1882 mi.^{2} of "R.Medium" @ 13 DU/A

1/"Town House Apts." only

2/Includes "Garden Apts.," Elevator Apts.," & "P.U.D."

1/Includes "Medium Density SF"

2/Includes "Townhouse" only

3/Includes "Gen. Res." & "P.U.D."

*(TOTAL WATERSHED AREA)/(AREA TRIB. TO SHIRLINGTON GAGE)/(AREA TRIB. TO ALEXANDRIA GAGE)

TABLE IV - III

NVPDC Breakdown of Land Use by Jurisdiction

(From WRE (1975))

ORIGINAL PAGE IS OF POOR QUALITY

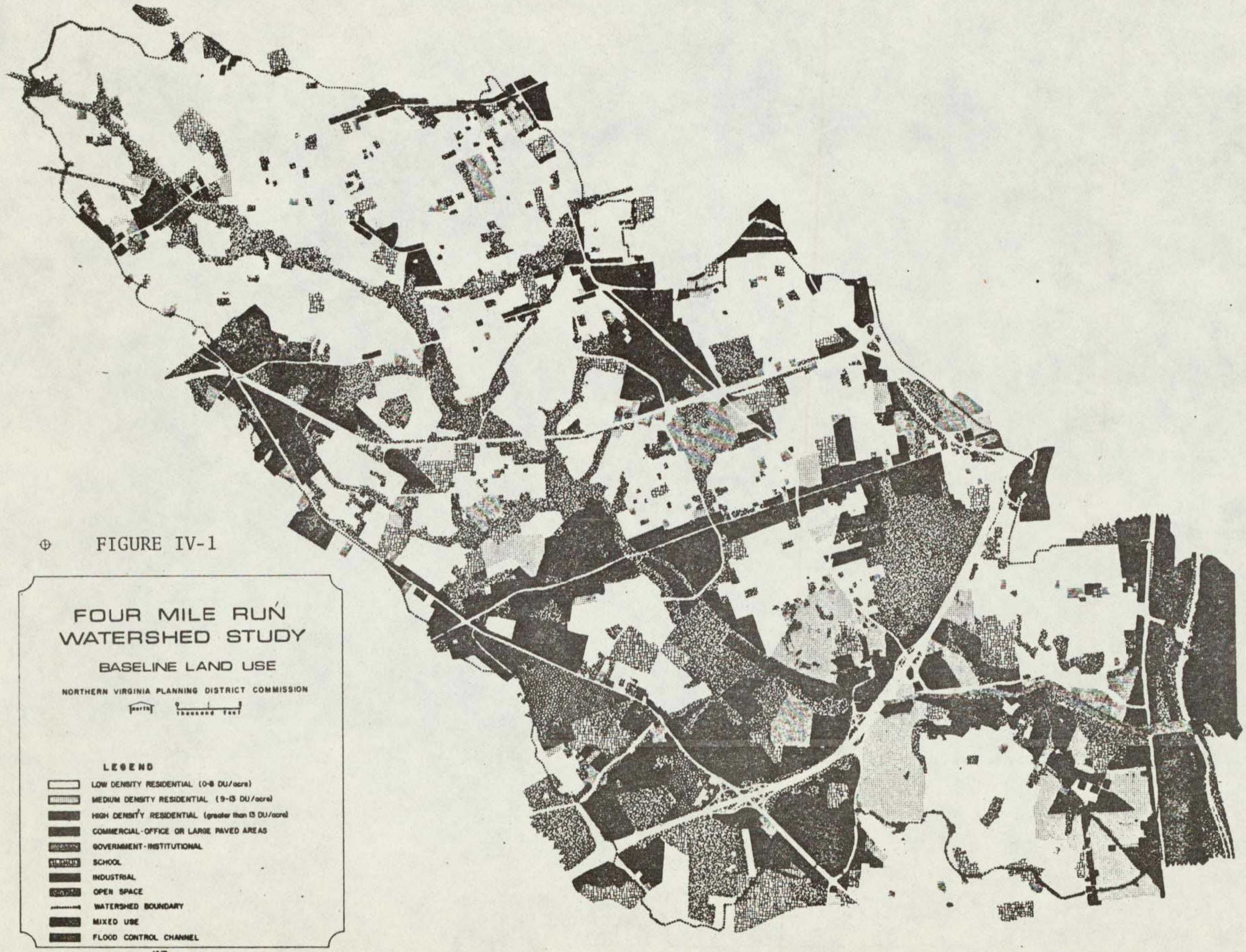

FOUR MILE RUN
WATERSHED STUDY
BASELINE LAND USE
NORTHERN VIRGINIA PLANNING DISTRICT COMMISSION
north
thousand feet
LEGEND
LOW DENSITY RESIDENTIAL (0-8 DU/acre)
MEDIUM DENSITY RESIDENTIAL (9-13 DU/acre)
HIGH DENSITY RESIDENTIAL (greater than 13 DU/acre)
COMMERCIAL-OFFICE OR LARGE PAVED AREAS
GOVERNMENT-INSTITUTIONAL
SCHOOL
INDUSTRIAL
OPEN SPACE
WATERSHED BOUNDARY
MIXED USE
FLOOD CONTROL CHANNEL

FIGURE IV-1

This composite runoff coefficient is calculated in STORM as:

$$C = \frac{\sum_{j=1}^{5} (C_p A_{p_j} + C_I A_{I_j})}{\sum_{j=1}^{5} A_j}$$

where C = the composite runoff coefficient,

C_I = the runoff coefficient for impervious area,

C_p = the runoff coefficient for pervious area,

A_{I_j} = the total impervious area in the jth land use category,

A_{p_j} = the total pervious area in the jth land use category,

A_j = the total area in the jth land use category, and

j = the land use category number.

The impervious runoff coefficient (C_I) and the pervious runoff coefficient (C_p) are the two principal variables adjusted during calibration. The pervious and impervious areas within each land use category must be established by detailed study. The NVPDC staff undertook a random sampling of each land use category in order to establish the amount of impervious area. The procedure was to estimate the percent impervious of each of these samples as the median value.

NVPDC sampled a total of 175 parcels of land within the watershed. The percent impervious was established using aerial photographs. Three classifications of impervious areas were measured for all land use classifications. The first group consisted of impervious areas which are most likely to be directly connected to the storm sewer system. This classification

included all streets. The second classification included impervious areas that are not always directly connected to the storm sewer system. This second group includes sidewalks, parking lots and drives in addition to the area in the first group. The third group consisted of all impervious areas, including those such as roofs which may not be directly connected to the storm sewer systems. Table IV-V shows the range and the average percentages for each group of impervious areas within each land use classification.

During major rainfall events the impervious area not directly connected to the storm sewer system (roofs) behave in some cases as if they were directly connected to the storm sewer system. As the magnitude of the storm events increases the amount of area that contributes directly to runoff increases. Since the present study is concerned with flooding events with a recurrence interval greater than five years all impervious areas were considered directly connected to the storm sewer system.

It should be noted that effort was focused on the residential land uses since residential land use dominates the watershed. One hundred thirty-six residential parcels were sampled and 39 parcels were sampled for all other categories. Of the total 19.5 square miles of the watershed, 15.5 square miles are in either residential or vacant land use categories. Industrial and commercial land uses are few in number but often occupy relatively large areas. The composite impervious area values for the five land use classifications used in STORM are presented in Table IV-VI.

TABLE IV-V

Land Use - Impervious Area Correlations

(From WRE (1975))

Land Use	No. of Areas Eval-uated	Total Area Square Feet	Size (1000 ft^2)		% Impervious Streets Only			% Impervious Streets, Drives, Walks, Parking			% Impervious Streets, Drives, Walks, Roofs, Parking		
			Min.	Max.	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Single Family	76	22,612,981.99	(100.7)	(1,116)	4.0	17.0	9.2	8.0	28.6	13.9	13.7	52.9	26.6
Medium Density Residential	14	3,285,318.68	(60.2)	(397)	5.8	11.2	7.6	10.9	56.7	19.2	22.7	65.0	34.4
High Density	46	24,358,927.25	(112)	(2,000)	2.0	20.2	7.7	11.9	52.6	31.1	30.9	73.2	48.3
Schools	9	8,339,239.65	(165.5)	(1,900)	2.6	7.9	4.2	13.0	29.0	17.9	23.2	49.4	30.8
Industrial	5	1,416,861.16	(143)	(483)	5.2	16.5	12.3	28.3	77.8	58.0	86.9	97.6	92.6
Commercial	15	4,338,743.5	(86.3)	(1,800)	5.0	23.8	12.1	59.6	86.9	73.6	71.8	99.7	94.2
Institutional	10	756,000.0	(27.0)	(185.4)	7.0	23.0	14.78	16.0	59.5	33.56	41.0	83.5	57.82

TOTAL 175 65,108,072.23 ⟶ 2.3 mi^2

TABLE IV-VI. Composite Impervious Areas for the Land Use Classifications in STORM

LAND USE	% IMPERVIOUS
Single Family, Residential and Schools	26.04
Multi-Family Residential	46.31
Commercial, Office and Institutional	83.00
Industrial	92.00
Vacant	8.00

Table IV-V is interesting because of the wide range in impervious percentage. Since vacant land has already been removed from each category, it is surprising that low density residential shows an impervious range of 13 to 53 percent. Medium density residential shows a range of 19 to 65 percent and high density a range of 31 to 71 percent. Although the averages are higher as density increases, as expected, the ranges greatly overlap.

B.3 *Cost and Manpower Requirements*

The land use distribution and percentages of impervious cover shown in Tables IV-III and IV-IV were developed by the staff of NVPDC. A detailed explanation of the procedues, times, and costs associated with the various sub-tasks was prepared by NVPDC and is presented as Appendix A.

Approximately fifty 1 in = 300 ft color aerial photographs, supplemented by extensive field checks, were used to develop the information. Development of the current land use was estimated at sixty man-days for the necessary air-photo interpretation, drafting, field checks, and planimetering. As stated earlier, 175 parcels of land within the watershed were selected for detailed study to determine the percent of imperviousness associated with each land use type. NVPDC estimated that fifty man-days were required to planimeter the impervious cover within these 175 parcels. Thus, approximately 110 man-days were required to develop the land use and imperviousness percentages needed for the operation of STORM. NVPDC estimated the cost of this effort at approximately $14,000.

C. PARAMETERS FOR STORM

C.1. *Runoff Coefficients*

In the model STORM the runoff coefficient is expressed as a ratio of the amount of rainfall which occurs as runoff to the amount of excess rainfall (rainfall in excess of the rainfall needed to fill depression

storage). Thus, the runoff coefficient is directly related to the infiltration capacity of the surface. The necessary runoff coefficients are for the broad categories of pervious and impervious areas.

Runoff coefficients for pervious and impervious areas in the model STORM were determined for storms with recurrence intervals greater than five years. The runoff coefficients will decrease as the magnitude of the storm decreases. Therefore, the runoff coefficients determined during the calibration process using large storms are not applicable for small storms with recurrence intervals less than five years.

The runoff coefficient is implicitly determined during the calibration process by an iterative process. For the initial calibration runs, runoff coefficients of 0.30 and 0.90 were assumed for the pervious and impervious areas, respectively. These values were altered during calibration until the peak discharge predicted by the model was approximately equal to the measured peak discharge for each of the seven selected calibration storms. It is impossible to exactly match all the peak discharges. Therefore, a pair of coefficients was selected to give the best fit for all storms considered in the calibration. These values were 0.90 and 0.39 for impervious and pervious areas, respectively. The runoff coefficients determined during the calibration are the values used in subsequent modeling with STORM.

C.2 *Depression Storage*

During any rainfall event some water accumulates in minor depressions and accumulates on plant foliage (interception). This rainfall does not occur as runoff and is simply held until it eventually evaporates after the storm. The term *depression storage* as used in STORM applies to all

water which is stored above ground and does not eventually occur as runoff. Depression storage is dependent on very localized phenomena such as condition of streets and type of cover.

The specific magnitude of depression storage has not been measured in the field because of obvious difficulties in obtaining meaningful data. Previous studies indicate a wide range of estimated values for depression storage (EPA(1971)). Depression storage used by other ranges from 1/16 to 1/2 inch for various runoff surfaces.

Previous studies using the model STORM indicate that a depression storage of 0.25 inches for Four Mile Run would be a reasonable estimate. This value is within the range of values used in other studies (EPA(1971)). The estimate of depression storage was tested by running the model STORM for the entire rainfall record of a year in which annual runoff volume was measured. As the continuous stage recorder was destroyed in the July 22, 1969, flood, yearly volumes of runoff are available only through water year 1968. The period selected for simulation was 1968.

Using runoff coefficients of 0.39 for pervious and 0.90 for impervious areas, depression storages of 0.25 and 0.125 inches yield runoff volumes of 14.16 and 17.00 inches (one inch of volume represents the volume of one inch of water over the entire watershed above the USGS gaging station), respectively for calendar year 1968. The USGS estimate of volume of stream discharge was 17.79 inches for calendar year 1968. STORM does not account for base flow (primarily groundwater discharge) but produces total volume for 1968 corresponds to an average daily flow[3] of 3.63 and 0.79 cfs for

[3]The volume of 1.00 inch of water over the entire watershed above the Four Mile Run gaging station is equivalent to the volume of water resulting from 1.00 cfs of runoff for an entire year.

storages of 0.25 and 0.125 inches, respectively. The difference between the total volume measured by the USGS and the direct runoff volume computed using STORM can be used as an estimate of the total yearly base flow volume. The average daily base flow rate of 3.63 cfs for a depression storage of 0.25 inches is within the range of the base flow (dry weather flow) at the USGS gaging station (3-7 cfs). Thus, a depression storage of 0.25 inches was used for subsequent modeling using STORM.

CHAPTER V

LANDSAT-BASED APPROACH USED TO DETERMINE LAND COVER AND ESTIMATE MODEL PARAMETERS

WRE's responsibility was to provide the best possible model for their client, the NVPDC. Thus, as described in the previous chapter, WRE used all of the available data, including streamflow records, to calibrate STORM. The thrust of the University of Maryland research was to test the utility of Landsat as a source of data for broad use in urban water resources planning models. In general, a consultant will not have extensive stream flow data for the particular watershed that he is investigating. Thus, the University wanted to examine Landsat performance under the general case where streams in the region would be gaged, but not the specific one under investigation. Therefore, the approach developed in this chapter is intended for use on ungaged watersheds. An optimal set of land cover related model parameters is developed for a region through analysis of the land cover-rainfall-runoff interrelationships for a series of watersheds in the vicinity of the basin being investigated. Landsat digital data is then analyzed by computer to determine the land covers within the watershed under investigation. This information allows the development of an estimate of the percent of imperviousness which, in turn, defines the parameters required for subsequent hydrologic simulation with STORM.

A. Development of Regional Parameters for STORM

The present investigation was concerned only with the runoff quantity component of STORM. The basic equation for the quantity model, repeated here

from Chapter IV, is:

$$Q = C\ (P-f)\ A \qquad \text{(V-1)}$$

Very little data is available that relates depression storage to watershed characteristics. Perhaps the most widely accepted procedure is that developed by Tholin and Kiefer (1959). In that study the suggested depression storage for previous areas was 0.25 inches and 0.06 inches for impervious areas. Thus, if a linear relationship is used the percent of imperviousness, IMP, is related to maximum depression storage by the following equation

$$f_{max} = 0.25\ (1.0-IMP) + 0.06\ (IMP) \qquad \text{(V-2)}$$

The composite runoff coefficient defined by Equation IV-2 can also be interpreted as

$$C = C_P\ (1-IMP) + C_I\ (IMP) \qquad \text{(V-3)}$$

where C_P = a runoff coefficient for pervious areas

C_I = a runoff coefficient for impervious areas

Seven watersheds in the Baltimore-Washington area were selected for use in analyzing the relationship between C and the percent of imperviousness. All of the watersheds had streamflow and precipitation gages and ranged in imperviousness from 25% to 100%. The pertinent data are listed in Table V-1. The data for watersheds 4, 5, 6 and 7 were obtained from a report by Terstriep and Stall (1974). The data for watersheds 1, 2 and 3 were obtained as part of the current study. The imperviousness for Little Falls Branch was estimated using Landsat data. High altitude color infrared photography was used in Watts branch and Henson Creek.

TABLE V-I

Sample Watershed Data

No.	Watershed Title	Area (Acres)	Percent of Impervious Area	Number of Events
1	Watts Branch	2368.00	250	3
2	Little Falls Branch	2624.00	334	2
3	Henson Creek	10688.00	322	3
4	Montebello No. 4	0.54	722	2
5	Gray Haven	23.30	520	4
6	South Parking Lot 1	0.39	1000	8
7	Tripps Run Tributary	322.00	31.0	6

The analysis was concerned with watershed response to events of high intensity and volume. In selecting the data for analysis an estimate of the watershed time of concentration was required. The peak intensity of a 2 year return period storm was a duration equal to the time of concentration was used as a guide in selecting events. Events used for the smaller watersheds had a minimum volume of 1 inch. The number of events selected for each watershed are included in Table V-I.

The maximum available depression storage for each watershed was estimated using Equation V-2 and the percent of impervious area values listed in Table V-I. For watersheds 4, 5, 6 and 7 the data on rainfall and runoff was available in the ILLUDAS report (1974). The published data was supplemented by the hourly precipitation gage records for Baltimore and Washington, D. C. Using this data, the antecedent conditions were established to determine the available depression storage.

For watersheds 1, 2 and 3 precipitation records for a number of prospective events were obtained for all of the hourly and daily stations in the area. The watershed average precipitation was calculated for each event using the gage network. The data was also used to calculate the watershed average antecedent conditions to adjust the maximum depression storage.

The computed watershed average rainfall was adjusted by the available depression storage and ratioed to the measured runoff to determine C for each event. For each watershed the C values were averaged to obtain a watershed C value. These values are listed in Table V-II.

TABLE V-II

WATERSHED RUNOFF COEFFICIENTS

WATERSHED NO.	OPTIMAL C VALUE	MODEL C* VALUE
1	0.444	0.462
2	0.547	0.490
3	0.506	0.492
4	0.706	0.712
5	0.594	0.603
6	0.862	0.855
7	0.456	0.498

*C value computed using a linear regression equation without that watershed included in the calibration data.

A linear regression equation was then used to develop the relationship between the C values and the percentage of impervious area. The linear regression equation has the following form

$$C = a + b \ (IMP) \ . \qquad (V-4)$$

The desired form of the prediction equation is

$$C = C_P \ (1-IMP) + C_I \ (IMP). \qquad (V-5)$$

By rearranging the terms of Equation V-5 it is equivalent to Equation V-4, as shown here

$$C = C_P \ + \ (C_I - C_P) \ IMP \qquad (V-6)$$

where

$$a = C_P \qquad (V-7)$$

and

$$b = (C_I - C_P). \qquad (V-8)$$

The "leaving-one-out" technique was used to develop the regression coefficients. In this procedure a linear regression equation is developed for each group of n-1 samples (n = the total available). The equation developed is used to predict the value of the sample left out. The final coefficients are computed by averaging each individual result. The correlation coefficient and standard error are computed using the samples that are left out.

The results of regression analysis are shown in Table V-II. The standard error was 0.024. The results show a good deal of stability in the relationship between C and IMP. However, it would be noted that a relatively small sample was used and the events used were only from heavy storms.

The final regression equation has an "a" term equal to 0.324 and and a "b" term equal to 0.538. The resulting equation relating C to the precent of impervious area is

$$C = 0.324\ (1\text{-IMP}) + 0.862\ (\text{IMP}) \tag{V-9}$$

The C_P = .324 and C_I = .862 determined from the seven watersheds in the region compare well with the recommendations of ASCE TM 23 (1974) and ASCE TM 24 (1974). TM 23 recommends a C_P between .1 and .3 and C_I between .8 and .9 when no other data are available. ASCE TM 24 presents a table which lists a runoff coefficient of 0.3 for a completely pervious area and 0.9 for an area of 100% imperviousness.

B. Development of STORM Parameters for Fourmile Run

In the use of the Landsat based approach for parameter development for ungaged watersheds, the maximum depression storage and runoff coefficients are defined by Equations V-2 and V-9 respectively. Both of these parameters require an estimate of the percent of imperviousness for the watershed. The percent of imperviousness for Fourmile Run was estimated from the April 9, 1973 Landsat scene for the Washington, D.C. using the Image 100 as described in Chapter II. Figures V-1 and V-2 are black and

LANDSAT IMAGERY
OF THE FOURMILE RUN AREA
SCENE 1260-15201 BAND 5
FIGURE V-1

LANDSAT IMAGERY
OF THE FOURMILE RUN AREA
SCENE 1260-15201 BAND 7
FIGURE V-2

white photographs of the false color infrared displays on the Image 100 CRT. The watershed boundary has been overlaid from the Input Scanner Unit shown schematically on Figure II-4. Figure II-3 illustrates the capability to overlay sub-watersheds where the light area is the area above the streamgage used for calibration of the conventional version of STORM.

Using the procedures described in Chapter II, training sites for the land cover classes listed in Table V-III were located and the scene classifed. Figure V-4 shows the CRT display of the distribution of the Highly Impervious/High Density Development within the watershed. Figure V-5 is a photo-reduction of the land cover distributions produced by the line printer of the Image 100.

Table V-IV is an Image 100 output of the distribution of the pixels assigned to each class within the gaged and total watersheds. These pixels were used to compute the percentages of the watersheds associated with each of the land cover classes listed in Table V-III. The percentages of imperviousness tabulated in Table V-III were obtained from a 728 pixel test site that was representative of the areas encountered in Four Mile Run. The details of the analysis of this test site are included in Appendix B. These representative inperviousnesses were used with Table V-IV to estimate the gaged watershed imperviousness as 39.1%. Equation V-2 was then used to estimate the maximum available depression storage to be 0.18 inches. Equation V-9 estimated C at 0.534.

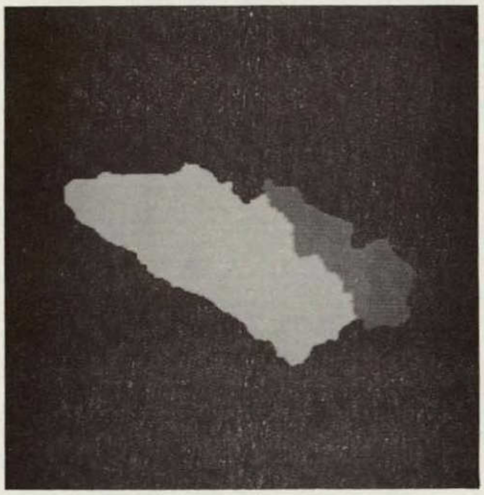


IMAGE 100 DISPLAY
OF THE FOURMILE RUN WATERSHEDS
(GAGED WATERSHED = WHITE)
FIGURE V-3

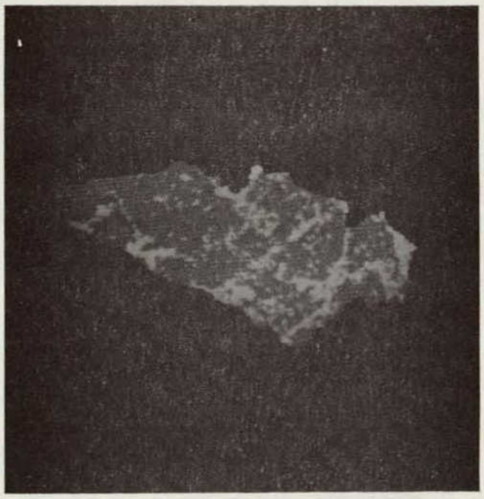


IMAGE 100 DISPLAY
OF HIGHLY IMPERVIOUS LAND USE IN
THE FOURMILE RUN WATERSHED
FIGURE V-4

FIGURE V - 5

Photo-reduction of Land Cover Distributions
Produced by Image 100 Line Printer

TRAINING GATE= 26620

ALARM= 0

THEME(1)=	34.	
THEME(2)=	359.	
THEME(3)=	579.	
THEME(4)=	2206.	
THEME(5)=	6821.	
THEME(6)=	258.	
THEME(7)=	7612.	- Gaged Subwatershed
THEME(8)=	10258.	- Total Four Mile Run

*** APEA ***

TRAINING GATE=	7612
ALARM=	0
THEME(1)=	32.
THEME(2)=	213.
THEME(3)=	405.
THEME(4)=	1502.
THEME(5)=	5212.
THEME(6)=	214.
THEME(7)=	7612.
THEME(8)=	10258.

TABLE V-IV

Distribution of Pixels Within Four Mile Run Watershed

(Retyped from Image 100 Output)

C. Comments on Percent of Imperviousness

As stated above, and described in Appendix B, sampling on a 728 pixel test site was used to define representative percents of imperviousness for the various land cover categories. This approach gave an estimate of 39.1% for the watershed imperviousness. If the representative values used by WRE in Table IV-VI had been used with the Landsat land cover distributions, the overall Basin imperviousness would have been estimated as 36.4%.

Sampling programs such as those described in Apendices A and B should be used to define percents of imperviousness if time and funds are available. Still, the literature summarizes the results of a number of surveys that can be used with reasonable confidence providing the urban structure is similar to that being considered. Table V-V shows several examples of representative imperviousness for the literature. If the Stankowski, (1972), Sopper and Loll (1969), or Boston values had been applied to Four Mile Run, the imperviousness would have been estimated as 34.9%, 38.1%, or 33.2% respectively. On the other hand, if the Santa Clara or San Francisco data had been used, the different structure of urbanization would have resulted in Basin imperviousnesses of 20.1% or 24.9%.

It should be noted that the percent of imperviousness values obtained by the NVPDC and the University of Maryland, as well as that of Stankowski (1972), exhibit a wide range for a given land cover. This behavior should cast serious doubts on the use of average values to estimate the

percent of imperviousness for a very small watershed. A ten acre single-unit residential area could be 12% or 40% imperviousness just as readily as it could be 25%. It is only when one deals with larger areas can he expect the actual percent of imperviousness to approach the mean.

TABLE V-V

Representative Imperviousness byLand Use Category

CATEGORY	PERCENT IMPERVIOUSNESS		
a) Sopper and Lull (1969)			
Cemeteries		5	
Parks and recreation		15	
Residential lot area:			
15,000 square		25	
6,000 to 14,999 square feet		40	
5,999 square feet		80	
Semipublic and public		75	
Industrial		90	
Commercial		100	
b) Boston Area			
Single-Family residental		25	
Multi-Family Residential		45	
Commercial		60	
Industrial		80	
Urban Open		10	
c) Stankowski (1972)	LOW	INTERMEDIATE	HIGH
Single-Family residential	12	25	40
Multiple-Family residential	60	70	80
Commercial	80	90	100
Industrial	40	70	90
Public and quasi-public	50	60	75
Conservational, recreational, and open	0	0	0

TABLE V-V (continued)

CATEGORY	PERCENT IMPERVIOUSNESS	
d) Santa Clara County and San Francisco (from ASCE-TM-23(1974))	Santa Clara County	San Francisco Bay Region
Residential:		
Hill areas	6	8
Low urbanization	10	15
Medium urbanization	20	25
Heavy urbanization (apartments)	32	40
Industrial:		
Nonmanufacturing	50	60
Manufacturing	40	50
Reserve	20	25
Commercial	50	60
Transportation	70	75
Public buildings	40	50
Public parks	12	12
Agricultural	4	4
Natural watersheds	2	2

CHAPTER VI

COMPARISON OF HYDROLOGIC SIMULATIONS USING STORM

The objective of the Fourmile Run Study was to test the utility of LANDSAT data as a tool in urban water resources planning in a real world situation. As stated before, the hydrologic model, STORM, was used to estimate flood flows and the frequency at which flows of a given magnitude would occur. Coupling the frequency of occurence information with the available data on economic losses allows estimates of annual monetary damages to be developed. The model can then be used as a screening tool to obtain a preliminary evaluation of how different flood control techniques would change the annual economic losses to the property owners in the watershed. The purpose of this chapter is to compare the results obtained with STORM calibrated with streamflow records and using land cover defined by conventional techniques with the version of STORM that was not calibrated and used parameters defined from Landsat land cover distributions.

A. Land Cover and STORM Parameters

Table VI-I compares the conventional and Landsat derived land cover requirements for the hydrologic model STORM. The table shows the percent of the gaged watershed assigned to each of the categories. Also shown are the representative percentages of imperviousness for each of the categories. The information shown in parentheses under the conventional and LANDSAT columns are from the more detailed breakdowns presented in Tables V-III, IV-VI, and V-IV.

The apparent discrepancy between the conventional and LANDSAT open space categories is illustrative of problems encountered when comparing

CONVENTIONAL

	% of Area	% of Imperv.
Low-Medium Density Development	61.1	30.9
(Single Family Residential and Schools)	(46.5)	(26.4)
(Multi-Family Residential)	(14.6)	(46.3)
High Density Development	16.6	83.7
(Commercial, Office & Institutional)	(15.2)	(83.0)
(Industrial)	(1.4)	(92.0)
Open Space	22.3	8.0
(Vacant)	(22.3)	(8.0)
Watershed Imperviousness		34.6

LANDSAT

	% of Area	% of Imperv.
Low-Medium Density Development	71.5	29.8
(Single Family Residential/ Low Density Development)	(68.6)	(28.3)
(Moderately Impervious/ Medium Density)	(2.9)	(64.9)
High Density Development	19.7	87.9
(Highly Impervious)	(19.7)	(87.9)
Open Space	8.8	5.8
(Bare Soil)	(0.5)	(0.2)
(Forest)	(2.9)	(5.2)
(Grass)	(5.4)	(6.6)
Watershed Imperviousness		39.1

TABLE VI-I

Land Cover and Percents of Imperviousness Estimated by Conventional and Landsat Based Approach

remotely sensed data with ground truth. Chapter IV explained that the MNVPDC assigned a portion of land parcels that were not developed to their fully zoned potential to the vacant land category. In this way, parts of residential areas that had densities less than that for which they were zoned would be assigned to the vacant land category. In the Landsat classification, all land with housing was assigned to residential or medium density development and only areas of bare soil, forest, or grass were considered as open space. Thus, the agreement in Table VI-I is not as good as that presented in Table II-II because the definitions used in the two parts of the study were simply different.

The overall watershed imperviousness estimated by the conventional techniques outlined in Chapter IV was 34.6%. The Landsat approach explained in Chapter V estimated the overall gaged watershed imperviousness at 39.1%.

Table VI-II compares the parameters and coefficients derived for STORM using the conventional and Landsat based techniques. It will be recalled that the parameters of the conventional approach were calibrated using land cover and stream flow records available for Fourmile Run. The Landsat derived coefficients assumed Fourmile Run to be an ungaged watershed and were developed from equation V-2 and V-9 and the imperviousness as estimated from the Image 100 analysis of the Landsat MSS digital data.

B. Stream Flow Characteristics

As explained in Chapter IV, the parameters for the conventional STORM were developed by calibration against six observed peak discharges. A seventh peak used to check the effect of antecedent moisture and the validity of the model for minor floods. The observed peaks and the best

TABLE VI-II

Parameters Used in Conventional and Landsat Versions of STORM

Parameter	Conventional Version	LANDSAT Version
Watershed Imperviousness (%)	34.6	39.1
C_P	.39	.32
C_I	.90	.86
C	.57	.53
f_{max}(inches)	.25	.18

estimates obtained with the conventional version of STORM are shown as Columns 2 and 3 of Table VI-III. The Landsat based coefficients presented in Table VI-II were input to STORM by WRE and run under the same rainfall conditions that were used to generate Column 3. The resultant peak discharges using the Landsat based coefficients are shown as Column 4 of Table VI-III. The peaks produced by the Landsat based STORM average 4.8% lower than those estimated with the conventional data. With respect to the observed peaks, the conventional and Landsat versions of STORM had standard errors of 15 and 17 percent respectively. Figure VI-1 is a graphical comparison of the peak discharge estimates using the two versions of STORM.

Despite what were considered to be extensive stream flow records on Fourmile Run, only two complete hydrographs were available for checking the performance of the model. Many hydrographs were available from the early years, but because of the extreme nature of the flooding under current land cover conditions, only two were available that were considered representative of the existing watershed for which the model was developed. Figure VI-2 illustrates the agreement between the observed runoff sequence and the simulated results obtained with the conventional and Landsat based versions of STORM. The relatively close agreement between the observed and simulated hydrographs is largely due to the extensive rain gage network described in Chapter II. Studies having limited rainfall often are unable to obtain the degree of agreement shown in Figure VI-2 because they cannot adequately define the average hourly basin precipitation.

As described in Chapter IV, the hydrologic model STORM was operated as a continuous streamflow generator using the hourly precipitation data from the raingage at National Airport as the input. The simulated peak discharges for each year were then used to develop a synthetic flood frequency curve.

TABLE VI-III
FOUR MILE RUN
COMPARISON OF CALIBRATION EVENTS

		DISCHARGE (cfs)	
EVENT	OBSERVED	WRE (1)	LANDSAT (2)
(1)	(2)	(3)	(4)
8/20/63	11,700	11,952	11,192
9/14/66	6,900	7,981	7,473
7/20/69	2,830	4,005	4,105
7/22/69	14,600	14,506	13,939
8/2/69	8,300	9,378	8,782
7/9/70	8,800	7,881	7,379
6/22/72	10,000	7,278	6,815

(1) "BEST FIT" BY OPTIMIZING VALUES OF COEFFICIENTS USED IN MODEL TO REPRODUCE OBSERVED PEAK DISCHARGES

(2) CONSIDERED WATERSHED TO BE UNGAGED, COEFFICIENTS DEVELOPED FROM WATERSHEDS IN THE VICINITY OF FOUR MILE RUN.

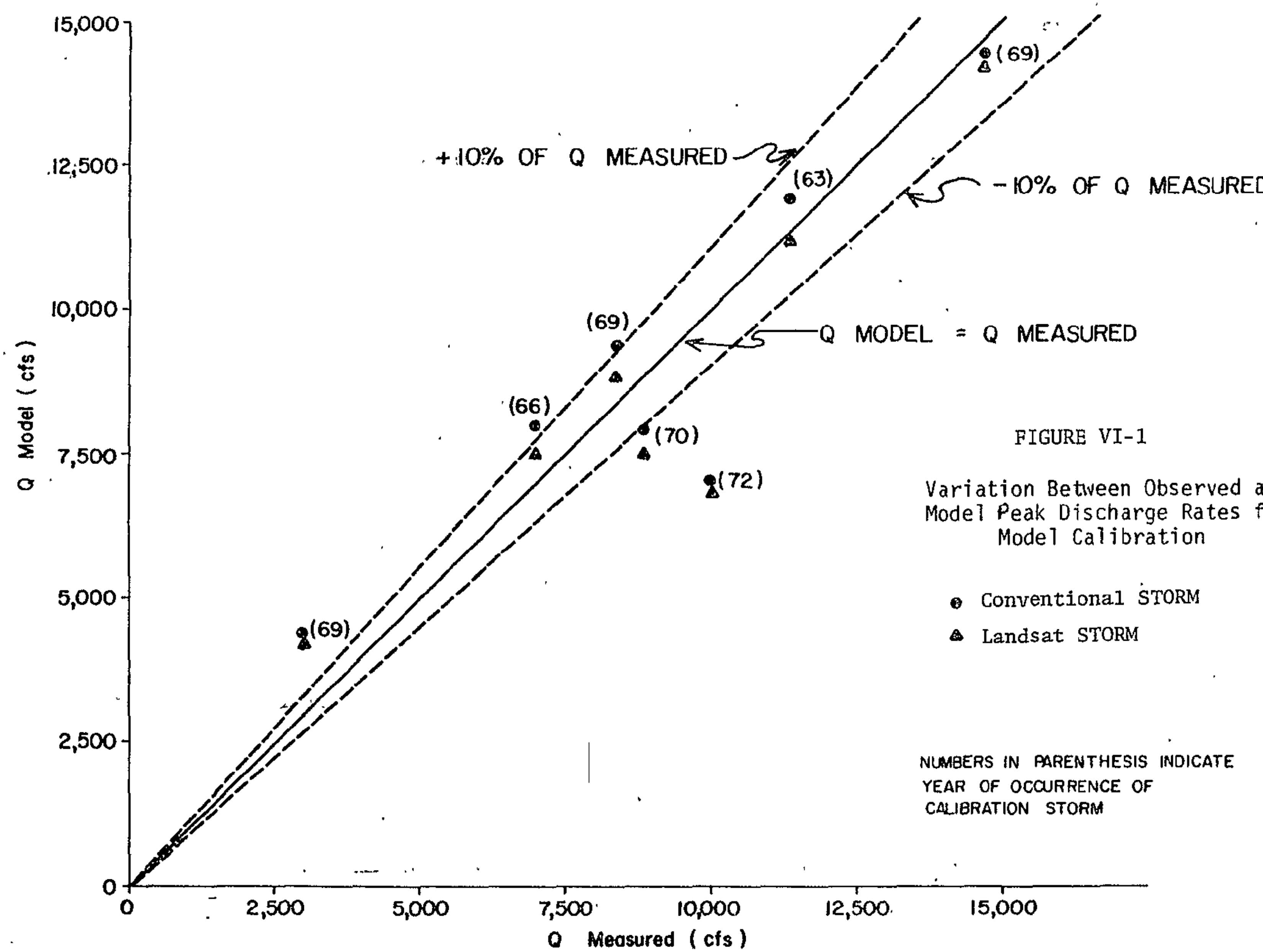


FIGURE VI-1

Variation Between Observed and Model Peak Discharge Rates for Model Calibration

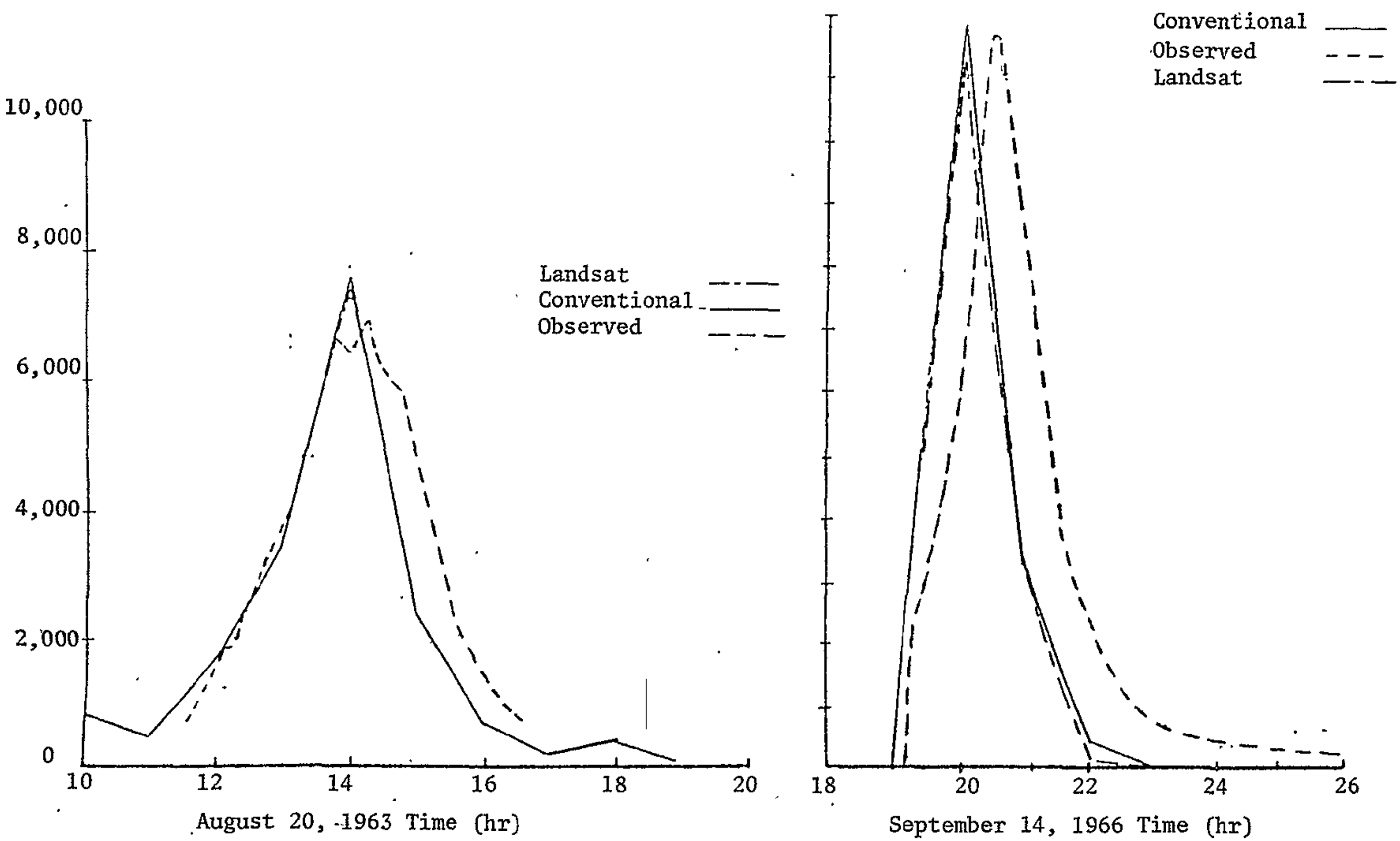


FIGURE VI-2

Four Mile Run Hydrographs

Figure VI-3 compares the curves developed with the conventional and LANDSAT versions of STORM with that developed from the stream gaging records. The agreement between the conventional and Landsat based versions of STORM is excellent. The departure between the synthetic flood frequency curves and that based on historic data is attributed to two problems. First, it was explained in Chapter IV that the runoff coefficient selected was optimized for large runoff events. Therefore, the runoff coefficient used probably overestimates the flows resulting from small rainfalls. Thus, the two year and perhaps the five year events would be higher than one would expect in nature. An attempt was made to correct this using a procedure described in Beard (1962).The second problem is that the historic data reflects many low flows that occurred prior to the intensive urbanization of the watershed.

C. Annual Damages Predicted by STORM

As explained in Chapter III, extensive data were available in the Four-mile Run watershed that related discharge of the stream to depth of flow and, in turn, the depth of flow to the economic losses that would occur.

Figure VI-4 shows how the flood frequency curve is related to the economic data to produce estimates of the annual damages caused by flooding.Figure VI-4 also shows how the differences between the conventional and Landsat versions of STORM were evaluated.

Information derived from the conventional version of STORM estimated the average annual damages caused by flooding of the watershed under its current condition to be $3,140,500. The Landsat based version of STORM estimated this figure to be 12.1% lower, $2,761,700. The conventional version of STORM estimated that the average annual damages would be reduced to $89,900 after the USACE flood control project is complete. The Landsat version of STORM estimated the annual damages to be $86,500 after the USACE project is completed

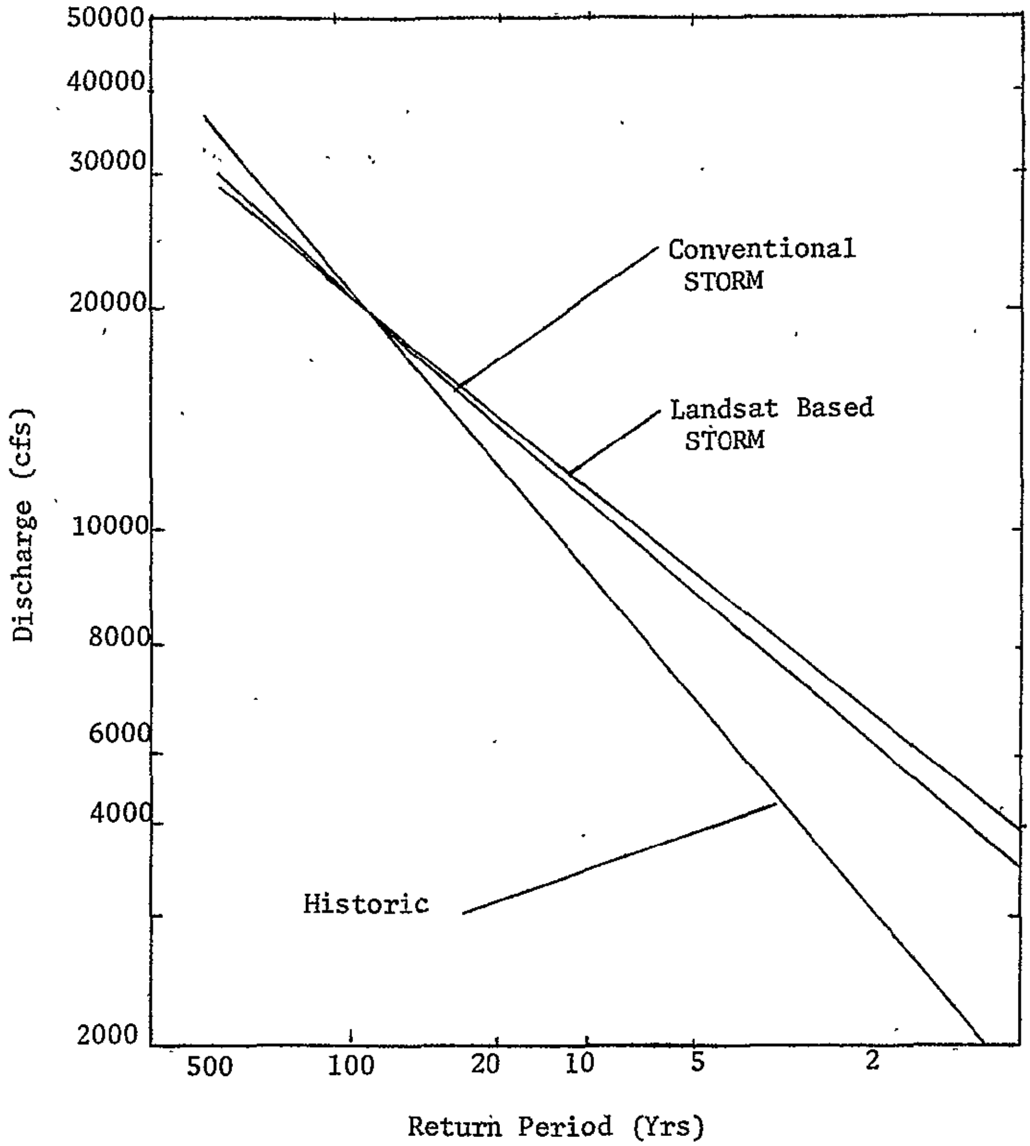


FIGURE VI-3

Four Mile Run Flood Frequency Curves

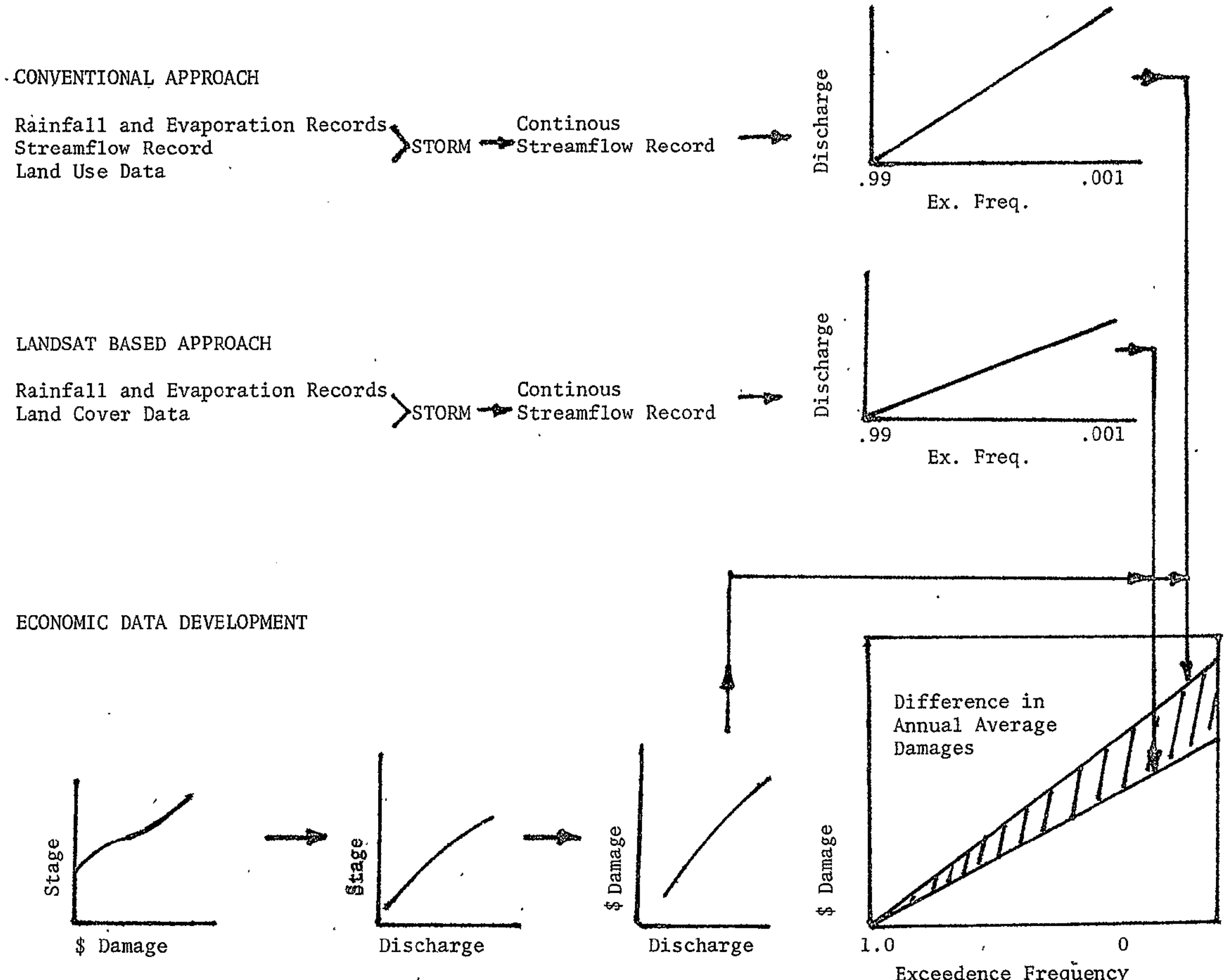


FIGURE VI-4
Outline of the Four Mile Run Comparison Study
(Based on Work Figure from Davis (1975))

Figure VI-5 shows the annual damages estimated by the two versions of STORM attributable to floods of a given return, with and without the USACE project.

As explained in Chapter III, STORM is intended as a planning model in hydrologic studies. In this context, it is used to give a preliminary "screening" of alternate flood control approaches. In this way, those techniques showing the most promise can be selected for more detailed evaluation, while those showing little or no impact can be discarded and thus avoid the cost associated with design evaluations. Table VI-IV shows the agreement between the conventional and Landsat based versions of STORM when used with a preliminary evaluation of detention storage as opposed to channelization in the Fourmile Run watershed. Detention storage under the conditions modeled would be simple overflow structures distributed within the watershed to provide the equivalent depths of detention indicated. Although the figures are slightly different, both versions of STORM show that relatively minor reductions in flood damages would be provided by using detention storage as the only flood control device in the watershed. However, both versions of the model show significant reductions when tested against the USACE project selected. The major point is that although the individual figures vary slightly, both versions of STORM indicate the same decision with respect to the direction to follow in flood control.

It must be recognized that Fourmile Run is a unique watershed and therefore cannot be considered as an indictment against detention storage. The major problem in Fourmile Run was the "choking" of the flow created by bridge openings and culverts at the lower end of the watershed that were designed when the landcover was primarily an agricultural and forested with little urbanization. In other watersheds not subject to such a condition, detention storage could logically be the appropriate solution.

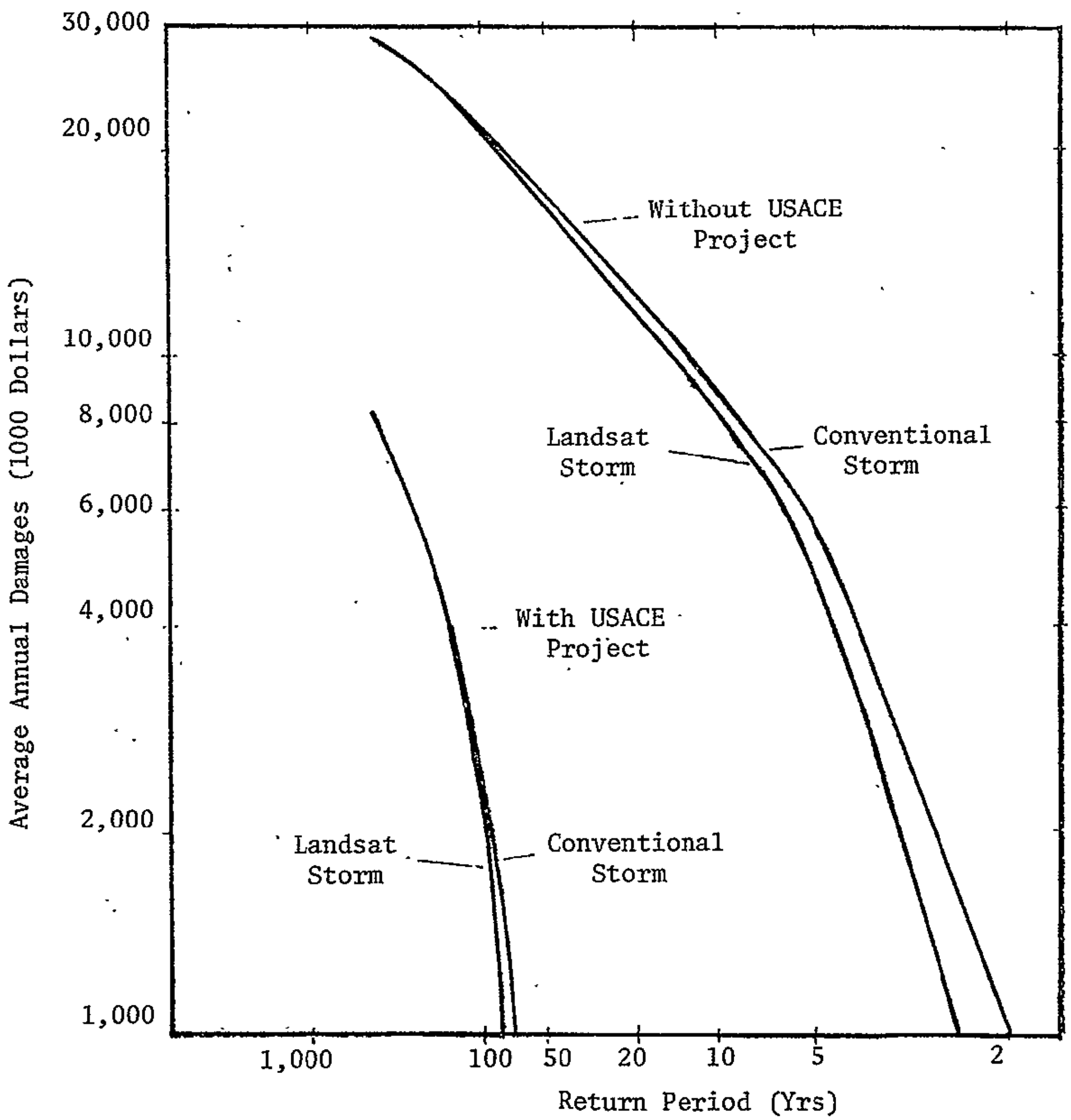


FIGURE VI-5
Four Mile Run Average Annual Damages Based on STORM Flood Frequency Data

TABLE VI-IV

IMPACT ASSESSMENT OF FLOOD CONTROL ALTERNATIVES
USING CONVENTIONAL AND LANDSAT-BASED STORM MODELS

ACTION		PERCENT REDUCTION IN ANNUAL DAMAGES	
		CONVENTIONAL STORM	LANDSAT-BASED STORM
Detention Storage (equivalent inches over the watershed)	0.10	3.7	4.8
	0.20	7.5	8.5
	0.30	10.6	11.8
Channelization, widen bridge openings, and remove culvert at railroad yard (USACE Project)		97.7	97.6

D. Cost and Manpower Associated with Land Cover and Parameter Estimation

As explained in Chapter IV and Appendix A, the NVPDC used 110 man-days at a cost of $14,000 to develop the land cover and percents of imperviousness required for the operation of STORM. The Landsat approach to defining the parameters required for STORM required 6.9 man-days, 2 hours of Image 100 computer time, with a total estimated cost of $2350. The hourly costs associated with the Landsat approach are representative of those used in the consulting engineering industry and include such items as estimates of overhead, fringe benefits, etc.

The $2350 figure used requires some clarification. First, the University of Maryland group that developed the parameters for Fourmile Run had used the Image 100 on other urbanized watersheds in the Washington, D. C. Area. Thus, some of the time associated with familiarization with the area, screening and ordering tapes from the EROS Data Center, developing techniques to locate sub-scenes, etc., were eliminated. If Fourmile Run had been the first watershed to have been studied in the Washington, D.C. region, approximately 18 man-days and 6 hours of Image 100 time would have been required for a total cost of the vicinity of $6,000.

CHAPTER VII

EXPERIMENTS WITH SUB-WATERSHEDS AND WREM

The agreement between estimates of discharge and economic losses developed from the conventional and Landsat versions of STORM was very good as described in the previous chapter. The agreement between land cover distributions, percent of imperviousness, and estimates of discharge reinforced the conclusions of Ragan and Jackson (1975, 1976), and Salomonson, et al (1975) that Landsat data could be used to define the parameters required for hydrologic planning models on a watershed basis.

In addition to comparing the results obtained with the conventional and Landsat versions of STORM on a watershed basis, the Four Mile Run study offered an opportunity to explore two additional questions that had been raised in the earlier studies by Ragan and Jackson (1975). First, as shown by Table II-III, the agreement between air-photo-estimated land cover and those estimates developed from Landsat decreases as the size of the area being examined decreases. When working with hydrologic models, one must recognize that the various models have different sensitivities to individual parameters. Thus, it was decided to further explore the errors associated with watershed size and to use Landsat derived data as inputs to the second model, WREM, being used by WRE in the Four Mile Run study. The Four Mile Run study provided an excellent opportunity for

this undertaking because, as explained in Chapter III, WRE was breaking the overall watershed into 179 sub-watersheds and using a design storm input to WREM to estimate point hydrographs within the watershed as well as design hydrograph at the lower end of the watershed.

A. Estimates of Percent of Imperviousness for Sub-Areas in the Four Mile Run Watershed

WREM is a much more sophisticated model than STORM and requires that an overall watershed be broken down into a number of sub-units. The use of WREM in Four Mile Run was based on consideration of the 179 sub-catchments shown in Figure VII-1. The average size of these catchments is 75 acres. As part of the overall study, the NVPDC developed land cover distributions and estimates of the percent of imperviousness for each of these sub-watersheds. The information prepared by NVPDC for each of these sub-watersheds included: (1) hydrologic soil types; (2) topography; (3) land use; (4) impervious cover; (5) storm sewer characteristics; and (6) channel characteristics.

Landsat data was used to estimate the percent of imperviousness for each of these sub-watersheds through the use of the alpha-numeric printout from the Image 100. The alpha-numeric printout was overlaid onto the Four Mile Run sub-watershed map through the use of an optical enlarger. It should be pointed-out that the over-laying had to be done for small portions of the watershed at a time because the geometric corrections for the alpha-numeric printout were not precise. The number of pixels assigned to each landcover category was compiled for

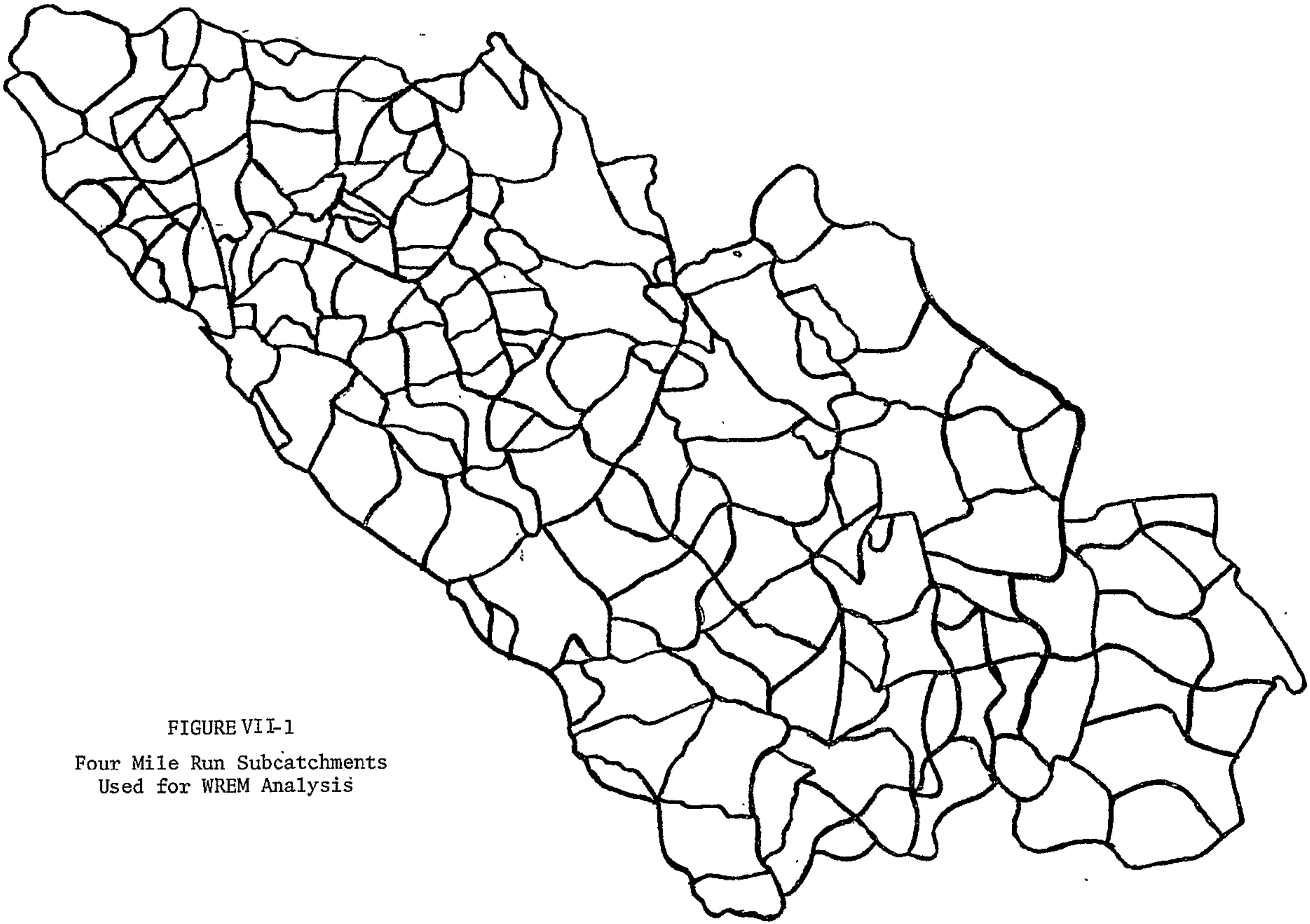


FIGURE VII-1

Four Mile Run Subcatchments
Used for WREM Analysis

each sub-watershed. These values were then used with the representative percents of imperviousness presented in Table V-III to compute to percent of imperviousness for the sub-watershed.

Table VII-I shows the standard error between the NVPDC estimate of percent of imperviousness and that obtained with Landsat. Although there are not enough samples within the various sub-watershed size categories to be statistically conclusive, the indications are that the error is substantial for very small areas and decreases as the size of the sub-watersheds becomes larger. One problem with the small watershed is the confidence of actually having the correct location of the watershed boundaries. As an example, when dealing with a watershed having five pixels in an urban land cover mixture, the decision as to which sub-watershed one or two pixels lie can throw large errors into the the percent of imperviousness of the adjacent watersheds. A second factor, is that there are simply not enough pixels in a very small watershed to adequately estimate the true distribution of the land cover.

Figure VII-2 shows the distribution of inlets and junctions used by WRE to route the sub-watershed hydrographs through Four Mile Run to the outlet. The inlets represent the confluence of several sub-watersheds. The junctions represent the downstream collection points of the inlets distributed along the major tributaries of Four Mile Run. There were 70 inlets and 20 junctions as part of the Four Mile Run version of WREM. Estimates of percent of imperviousness were made for each of the inlets by accumulating the information of contributing sub-watersheds. The same

TABLE VII-I

PERCENT OF IMPERVIOUSNESS ERROR

AS A FUNCTION OF CATCHMENT SIZE

Catchment Size (Range in Pixels)		No. of Catchments	Std. Error (%)
0.	20.	34	24.25
20.	40.	47	14.53
40.	60.	28	13.89
60.	80.	17	10.22
80.	100.	11	10.88
100.	120.	11	10.51
120.	140.	5	10.82
140.	160.	3	10.29
160.	180.	2	7.39
180.	400.	6	7.39

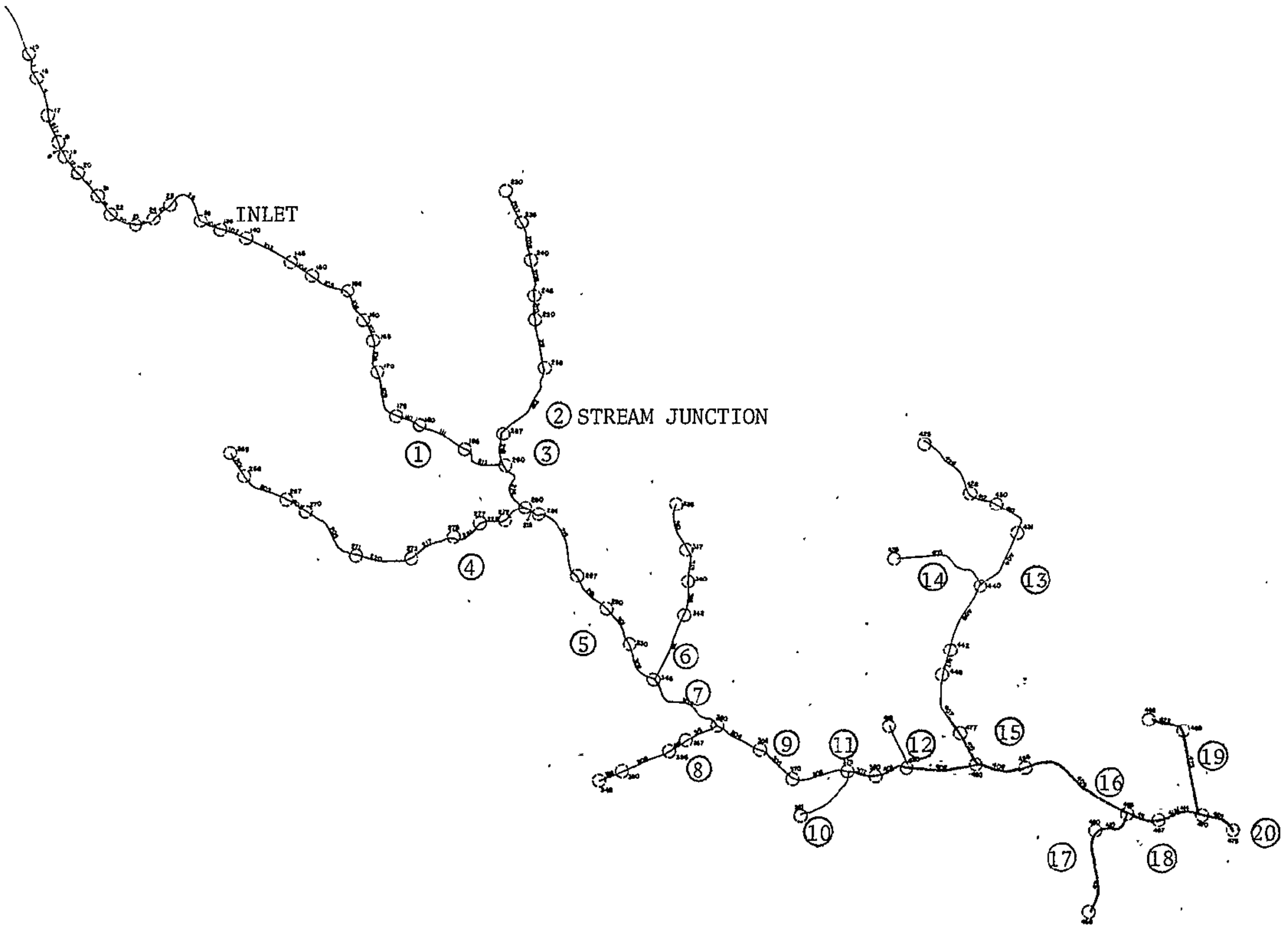


FIGURE VII-2

Four Mile Run Inlets
and Stream Sections

was done for the junctions by considering the cumulative effect of the inlets contributing to each junction. Table VI-II presents information describing the sub-categories and the standard error in the percent of imperviousness for each category. Again, as the average size of the unit being considered increases the standard error in the estimate of imperviousness decreases. TableVII-III shows the reduction in the difference between the NVDPC and Landsat estimates of percent of imperviousness as one adds junctions to the area being considered.

B. Comparison of Discharge Hydrographs Computed with WREM

As stated earlier, WREM is a much more sophisticated model than STORM Briefly, the model converts land use into a percent of impervious cover for each sub area. In the present case, the rainfall input was a design storm developed to simulate a hundred-year rainfall event. WREM translates the design storm rainfall into overland flow by substracting infiltration and depression storage. The overland flow is then routed through minor sections of the man made and natural drainage system. In this way, a runoff hydrograph is computed for each sub-watershed. These runoff hydrographs are then collected at the inlets and routed through storm sewers or channels to the junctions. A third module of WREM then routes these flood flows through the major sections, either man made or natural, of the watershed to obtain flood hydrographs at points along the system and at the downstream end of the watershed. For detailed describtion of the use of WREM in Four Mile Run, the reader is referred to Fitch, Hartigan, and Iwanski (1976).

TABLE VIII

Four Mile Run Error Analysis

For the Percent of Impervious Area

LEVEL	CATCHMENTS	INLETS	JUNCTIONS
Number of Samples	179	70	20
Average Size (Pixels)	65.5	145.3	524.6
Size Standard Deviation	53.9	107.0	550.5
Size Range	5-236	6-482	26-2582
Standard Error (%)	14.9	11.0	6.5

TABLE VII-III

CUMULATIVE BEHAVIOR OF ERROR IN PERCENT OF IMPERVIOUSNESS

SUMMARY

JUNCTION ADDED	PERCENT IMPERVIOUS CUMULATIVE NVPDC	PERCENT IMPERVIOUS CUMULATIVE LANDSAT	AREA CUMULATIVE (PX)	DIF.
1	23.20	30.30	2582.	7.1
2	26.64	31.83	3390.	5.2
3	26.54	31.90	3422.	5.4
4	28.24	33.52	3915.	5.3
5	30.33	35.63	4937.	5.3
6	30.81	36.60	5508.	6.0
7	30.86	36.63	5527.	5.8
8	31.12	37.83	6318.	6.7
9	31.61	38.28	6642.	6.6
10	31.97	38.42	6969.	6.5
11	32.45	38.80	7315.	6.4
12	32.74	38.88	7501.	6.4
13	32.84	38.89	8072.	6.2
14	33.18	39.13	8329.	5.9
15	33.20	38.77	8723.	5.6
16	33.34	36.72	9072.	5.4
17	33.54	38.85	9491.	5.3
18	33.75	39.88	9702.	5.3
19	34.02	39.88	9951.	5.1
20	34.84	39.88	10177.	5.0

The University of Maryland supplied WRE with the Landsat based estimates of percent of imperviousness for each of the 179 sub-watersheds. Following the same philosophy as had been developed in the study with STORM, WRE then operated WREM with the Landsat based data in the same manner that it followed using the NVPDC estimates. Table VI-IV shows the agreement between the peak discharges estimated for the 179 sub-watersheds using WREM based own MVPDC data and Landsat data. The data indicated that the Landsat data was unable to satisfactorily estimate the peak discharges for the individual sub-watersheds.

Figure VII-3 shows the design hydrographs at the watershed outlet that were computed using WREM and the MVPDC and Landsat data. Now, the area being considered is the cumulative effect of the 50.5 sq. km (19.5 sq. mi.) drainage area upstream from that point. The difference of the two peaks is only 7.4%. Similarly, the design hydrograph computed with WREM at the Alexandria gage which drains 37.0 sq. km (14.3 sq. mi), show peak discharges of 20,408 cfs with the Landsat data and 18,954 cfs with the conventional data or a difference of 7.7%. Again, it appears that when large areas are involved, the estimates developed by Landsat compare very well with those from conventional data.

It is important to recognize that the percent of imperviousness is only one small part of the input data required for WREM. The time and effort required to assemble information on storm sewer location, sizes, slopes, street gutter geometry, links of over land flow, infiltration estimates, geometry of natural channels, etc., could be several orders of

Interval size in acres	Number of samples	Average size of samples in acres	NVPDC average discharge in cubic feet per second	Standard error of discharges as a percent of the mean
0 - 40	64	24.7	101.6	44.
0 - 80	125	39.1	162.1	29.
0 - 120	148	48.8	192.1	27.
0 - 160	164	58.7	230.2	25.
0 - 265	179	69.7	267.0	23.6

TABLE VII-IV

STANDARD ERROR OF LANDSAT BASED WREM DISCHARGES

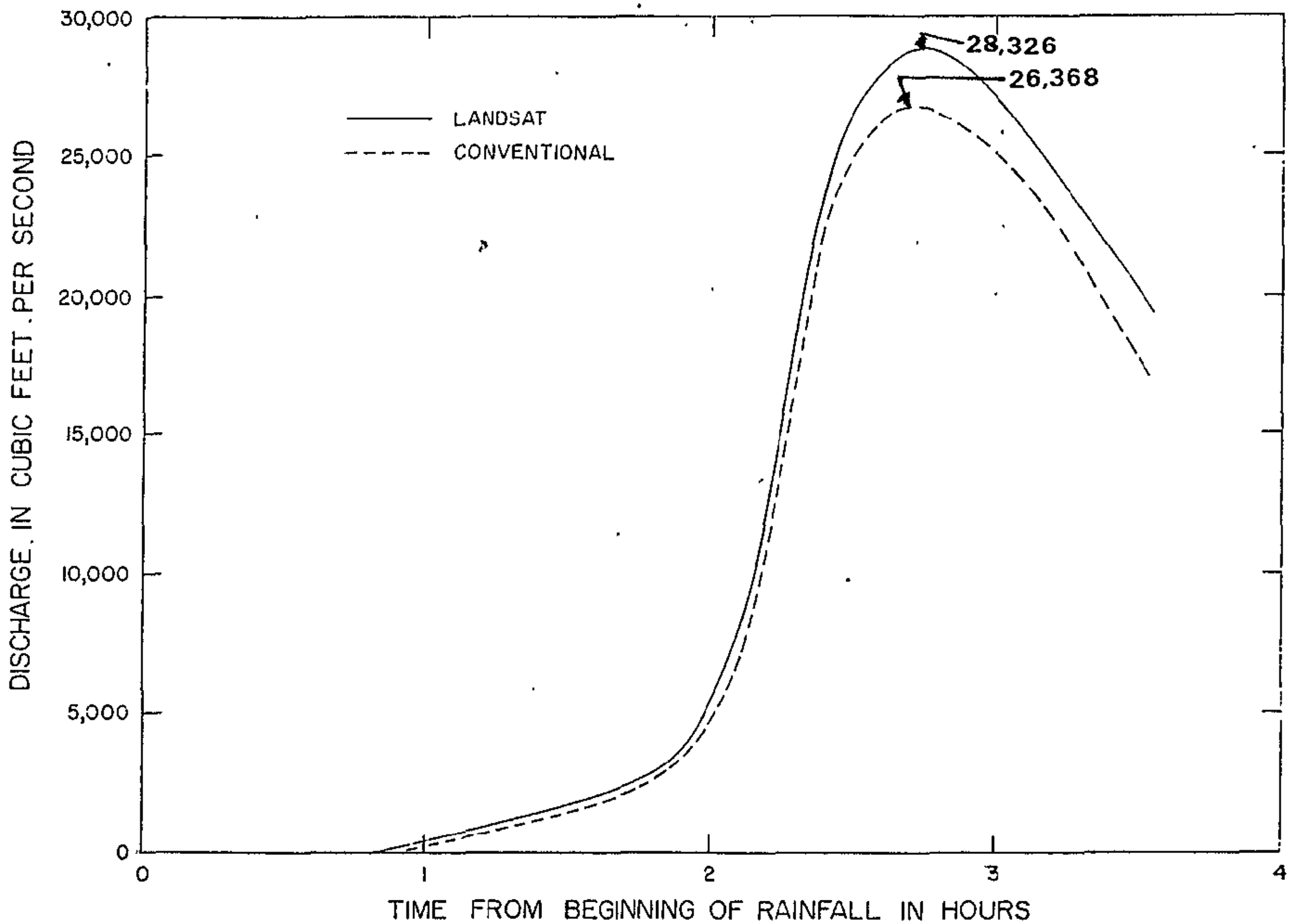


FIGURE VII-3

Four Mile Run Design Hydrographs
Estimated With WREM

magnitude greater than that required for the land cover estimates associated with the percent of imperviousness. Thus, when using a detailed design model the structure of WREM, any gains achieved through the use of Landsat as opposed to conventional landcover data could be minor.

C. SUMMARY

When it is necessary to consider small areas, perhaps less than one square mile, the current state of the art indicates that some remote sensing techniques other than Landsat will be necessary to develop the land cover estimates required for hydrologic modeling. There are definite needs for more studies on the statistics associated with errors related to multiple land cover distributions and size of area being examined. As geometric corrections to the Landsat data improve, it is possible that the size of the sub-watersheds that can be examined will be reduced. Still, even when using conventional land cover determinations, one must recognize that different interpreters will disagree on cell classifications within the area with resulting point errors as shown by Jackson and Ragan (1976).

The real advantage of Landsat is gained when working with larger watersheds. The maximum utility would be to an organization that must work with many watersheds within a large area of jurisdiction. In such an approach, considerable economic and manpower savings can be achieved by classifying the entire area of jurisdiction, storing it on a conventional computer in the form of a matrix, and then accessing the required modeling information by entering the coordinates of the watershed boundaries. An example of such an approach is that presented by Shieker (1976)

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APPENDIX A

APPROACH USED BY NVPDC TO DETERMINE LAND COVER DISTRIBUTIONS AND ESTIMATE AVERAGE AVERAGE PERCENTS OF IMPERVIOUSNESS*

I. LAND USE DETERMINATIONS

a. Aerial Photos (Arlington County with sufficient coverage of other 3 jurisdictions)
   - Color prints
   - SCALE: 1"=300'
   - Approximately 50 photos required for watershed coverage.

b. Land Use Maps
   - Manpower requirements
     - o Mapping: 5 man-weeks aerial photograph interpretation (to convert future land use plans to existing land use maps and to define open space categories that meet attached impervious % criteria); 2 man-weeks for draftsman's effort; 3 man-weeks for field checks. TOTAL COSTS: Approximately $6,500.
     - o Planimetering Map: for entire watershed = 2 man-weeks. TOTAL COSTS: Approximately $1500.

II. IMPERVIOUS COVER DETERMINATIONS

a. Sampling Program
   - Residential land uses
     - o Isolate all major residential development projects in watershed (e.g., subdivisions, townhouse cluster, etc.).
     - o Identify a "typical" block or cluster of residential units within each development project (i.e., a block or cluster that has impervious cover characteristics which are typical of the surrounding blocks or clusters in the development project.).
     - o Planimeter total impervious cover shown on Arlington County aerial photos (streets, drives, walks, roofs, parking) for typical block or cluster: see WRE "Hydrology Report" for tabulations.

*Provided by Mr. J. P. Hartigan, Planner/Engineer, Northern Virginia Planning District Commission, Falls Church, Virginia

- Commercial-Office, Industrial, Institutional

    - o Planimeter "typical" projects in each jurisdiction (for all of above except churches).

    - o For churches, planimeter typical projects with off-street parking facilities and compare with typical projects that must rely upon on-street parking.

b. Determinations for Model "STORM" Applications
- Residential land uses

    - o Determine number of acres in each major density category (for single family) or zoning category (for medium density and high density) by jurisdiction.

    - o Define median value for impervious cover samples in each density or zoning category by jurisdiction (See Attachment).

    - o Compute weighted average for "impervious cover %" in each manor land use category for entire watershed.

c. Determinations for Model WREM Applications
- Define 49 impervious cover "districts" for watershed that are based upon results of sampling program and zoning map.

    - o Assign sample site's impervious cover % to surrounding projects with similar zoning classifications.

    - o Define weighted average impervious cover % for each land use category in each district.

d. Manpower Requirements: 10 man-weeks. TOTAL COST: Approx. $6000

III. MOTIVATIONAL REQUIREMENTS

It was difficult to keep technicians motivated for an extended period of time, particularly in the case of impervious % planimetering. From experience, we learned that technicians that are given a significant amount of independence (i.e., allowed to choose data sets that they will work on in any given day and permitted to alternate between two or more data sets (on an hourly basis, if necessary) in order to relieve boredom and prevent fatigue) will be the most productive in the long run.

Personalitites also play a prominent role. We were very fortunate to have a highly dedicated technician performing the work.

APPENDIX B

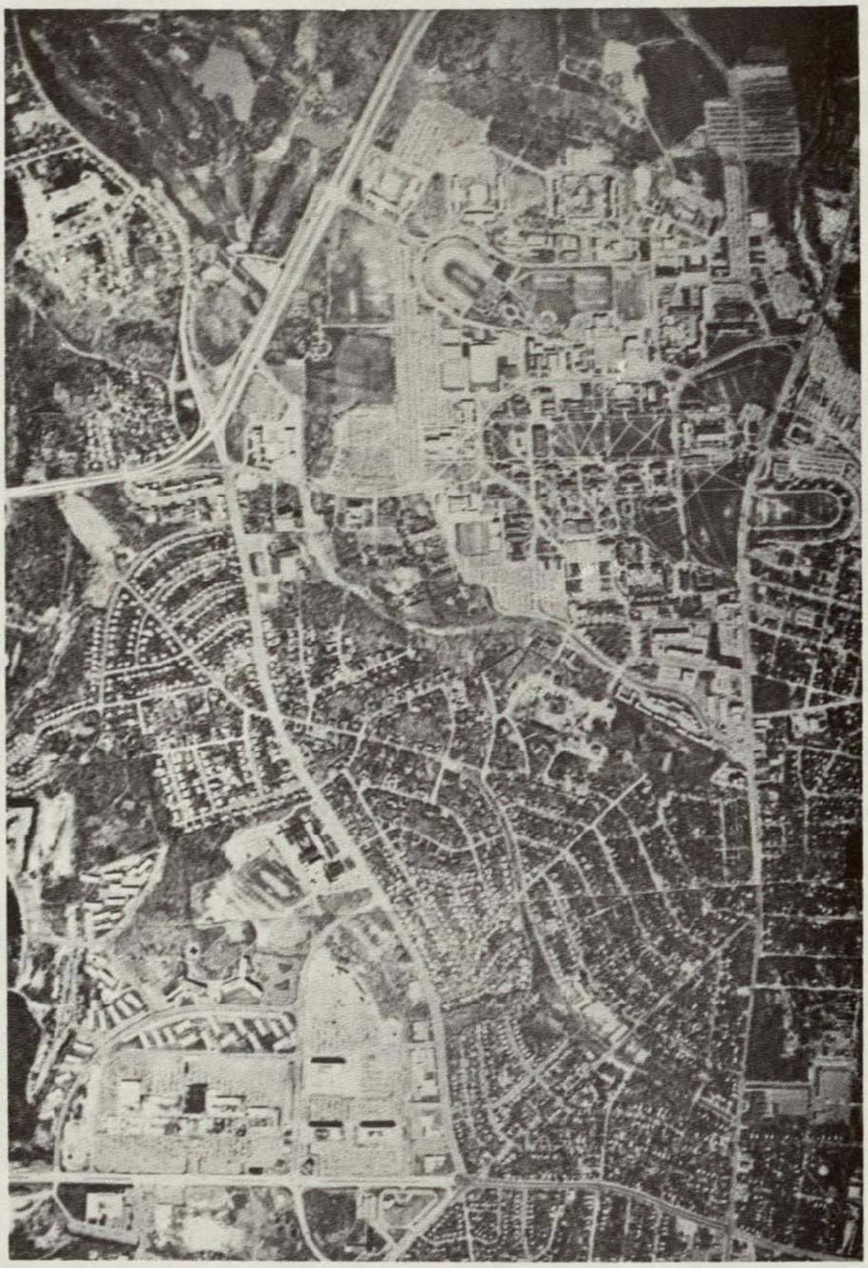
DETERMINATION OF AVERAGE PERCENTS OF IMPERVIOUSNESS FOR LANDSAT DERIVED LAND COVER CATEGORIES

A test site of 728 pixels was chosen for study. The site is located, in the northeastern suburbs of Washington, D.C., south of the University of Maryland and north of East-West Highway. Low altitude 1:4800 black and white photography, April 1972, supplemented with 1:24,000 color infrared U-2 photography, April 1974, served as ground truth. The Landsat data were obtained during previous studies of scene 1260-15201, April 1973. Figure B-1 is a photograph of the test site mosaicked from the 1:4800 black and white photos. Figure B-2 is a black and white reproduction of the U-2 photographs.

A mylar overlay of 28 x 26 pixels was used to define the approximate boundaries of the test site on the 1:4800 photos. The overlay was split into six sections and each section was positioned using the Landsat data for several unique pixels (i.e., concrete parking lots).

Two types of ground truth data were obtained. First, each pixel was classified by photo interpretation of the 1:4800 photos into one of the seven land use categories described in Table B-I. It was necessary to create an unclassified category because of several small water bodies in the test site. The interpretation of the photos is considered accurate because of familiarity with the area, the fact that small variations in the pixel location do not change the classification and that the categories used are easily determined on 1:4800 photos.

next, a smaller grid consisting of 238 units was overlayed on each pixel. Each of the 238 units was classified as either pervious or impervious and those identified as impervious were summed to obtain the percent of impervious area. Small variations in the pixel location will change the estimate of the percent of imperviousness. However, by using a large number of units for each pixel it is believed that the effect was minimized.



REPRODUCTION OF BLACK AND WHITE 1:4800
AERIAL PHOTOGRAPHS SCALE 1:22,000

Figure B-1

BLACK AND WHITE REPRODUCTION OF NASA
COLOR INFRARED PHOTOGRAPH SCALE 1:72,000

Figure B-2